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Electricity Power Planning in Portugal: The Role of Wind Energy

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ELECTRICITY POWER PLANNING IN PORTUGAL: THE ROLE OF WIND ENERGY

Abstract

Energy decisions play a major role in the achievement of sustainable development and consequently on the economic, environmental and social welfare of future generations. Combining energy efficiency with renewable energy resources constitutes a key strategy for a sustainable future, emphasised in the European and Portuguese policy guidelines. The wind power sector stands out as a fundamental element for the achievement of the European renewable objectives.

Currently, most of the energy planning models focus predominantly on the economic and environmental dimensions of the problem. Although recognised as important, the social aspects of energy decisions are not fully integrated into the available decision aids for planners. The main contribution of this thesis is to provide a new integrated tool for decision makers engaged in long term electricity planning. An Integrated Electricity Planning Model (IEPM) was developed accommodating environmental, economic and social issues. The proposed approach involves complex optimisation models for cost, and emissions objective functions based on the mathematical description of the electricity system. Linear and non-linear optimisation models were developed establishing the link between the cost of generation and CO_2 emissions. In addition, a value judgment assessment of each of the possible generation technologies was obtained by a combination of Delphi and Analytic Hierarchy Process to develop Social Indices for the proposed technologies. From these models possible generation plans are developed for a 10 year planning period, and their financial, CO_2 emissions and social impacts are assessed and fully integrated into the final optimising decision tool.

For the implementation of the IEPM, details of the Portuguese electricity system were obtained from official sources and from experts' collaboration. According to the official reports, the increasing demand for electricity in Portugal over the next ten years will be mainly supported by new investments in coal, natural gas, wind and hydro power technologies.

The rising trend of the installed wind power is analysed resulting in new insights that demonstrate the need to address the impact that energy sources with variable output may have, not only on the short-term dispatching process, but especially on the medium to long range planning activities.

The study of the Portuguese case concludes that while wind power influences significantly the power system operation and it is not free of negative social impacts, it has a fundamental role in future electricity plans, particularly in regard to meeting the renewable and Kyoto protocol commitments.

Although it was applied to Portugal, the proposed methodology may be used in other regions or countries if adapted to the specific features of each individual energy system under analysis.

On the whole, the proposed methodology gives the decision maker a better understanding of the system characteristics and of the full impact of possible decisions, and in doing so, makes a valuable contribution to the selection of long term sustainable energy plans.

Keywords: Electricity planning models; energy decisions; wind energy; cost-environmental-social models.

PLANEAMENTO DO SISTEMA ELÉCTRICO EM PORTUGAL

Resumo

As decisões no sector energético têm um papel fundamental na consecução de um desenvolvimento sustentado, influenciando decisivamente o bem estar económico, ambiental e social das gerações futuras. A combinação da eficiência energética com fontes de energia renováveis representa uma estratégia chave para um futuro sustentado, enfatizada nas políticas orientadoras Europeias e Portuguesas. O sector eólico destaca-se como um elemento essencial na concretização dos objectivos traçados para as energias renováveis ao nível da União Europeia.

Actualmente a maioria dos modelos de planeamento energético centram-se predominantemente nas dimensões económica e ambiental. Apesar de reconhecidamente importantes, os aspectos sociais não estão ainda totalmente integrados nos sistemas de apoio à decisão aplicados ao sector da energia. A principal contribuição desta tese é a de dotar os decisores de uma nova ferramenta para apoio ao planeamento eléctrico de longo prazo, integrando variáveis ambientais, económicas e sociais. A abordagem apresentada envolve modelos complexos de optimização de funções objectivo custo e emissões, baseadas na descrição matemática do sistema eléctrico. Foram desenvolvidos modelos de optimização linear e não linear, estabelecendo-se a relação entre os custos de produção de energia eléctrica e emissões de dioxido de carbono associadas. Adicionalmente, a combinação do método Delphi com o Processo de Análise Hierárquica permitiu estimar e analisar julgamentos de valor relativamente aos impactos das possíveis tecnologias de geração de electricidade, resultando em Índices Sociais associados a cada uma destas tecnologias. A partir destes modelos são desenvolvidos possíveis planos para geração de electricidade para um período de 10 anos, sendo os respectivos impactos sociais analisados e integrados na decisão final.

A implementação do Sistema Integrado para Planeamento Eléctrico, implicou uma recolha detalhada de informação relativa ao sistema eléctrico Português recorrendo a fontes oficiais e a especialistas na matéria. De acordo com os relatórios oficiais, o aumento de consumo de electricidade em Portugal durante os próximos 10 anos, será essencialmente suportado por novos investimentos em centrais a carvão, gás natural, energia eólica e hídrica.

O esperado aumento da potência eólica instalada é analisado, demonstrando-se a necessidade de considerar o impacto que as fontes energéticas de produção variável terão, não apenas na gestão de curto prazo do sistema eléctrico, mas especialmente no planeamento a médio e longo prazo.

Do estudo do caso Português conclui-se que a energia eólica tem um impacto significativo ao nível da gestão das operações do sistema eléctrico e não pode ser considerada livre de impactos sociais adversos. No entanto, a energia eólica tem também um papel fundamental no futuro sistema eléctrico Nacional, particularmente para atingir as metas traçadas pelo protocolo de Kyoto e pela Directiva Europeia das energias renováveis.

Apesar da metodologia proposta ter sido aplicada ao caso Português, poderá ser aplicada a outras regiões ou países tomando em linha de conta as particularidades de cada sistema energético em análise.

Na globalidade, a metodologia proposta permite que o decisor reconheça e entenda de forma clara as características do sistema e os impactos que as possíveis decisões acarretarão, contribuindo assim para a selecção de planos energéticos de longo prazo consistentes com os princípios do desenvolvimento sustentado.

Palavras chave: Modelos de planeamento eléctrico; Decisões energéticas; energia eólica; Modelos custo-ambiente-impacto social.

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Abbreviations and nomenclature

A- Matrix of judgments

AC- Annualised cost

AHP- Analytic Hierarchy Process

APERC- Asia Pacific Energy Research Centre

ASI- Average Social Index

BARON- Branch and Reduced Optimisation Navigator

BB- Branch and Bound

C- Total present value of cost (€)

CCGT- Combined Cycle Gas Turbine.

CI- Consistency Index

CO- Total CO_2 emissions (ton)

CO_2- Carbon dioxide

$COEF_{2t}$- CO_2 specific emission factor of candidate CCGT in year t (ton/MWh).

$COEF_{5t}$- CO_2 specific emission factor of existing CCGT in year t (ton/MWh).

$COEF_k$- CO_2 specific emission factor of k type power plants (ton/MWh).

$COEF_l$- CO_2 specific emission factor of l type power plants (ton/MWh).

$COEF_{sj,x}$- CO_2 specific emission factor of power plant x for the hourly step j of week s (ton/MWh).

$(COEF_{5t})_a$- CO_2 emission factor for generating 25% of electricity supplied by existing CCGT in each month of year t (ton/MWh).

$(COEF_{5t})_b$- CO_2 emission factor for generating 50% of electricity supplied by existing CCGT in each month of year t (ton/MWh).

$(COEF_{5t})_c$- CO_2 emission factor for generating the remaining 25% of electricity supplied by existing CCGT in each month of year t (ton/MWh).

$(COEF_{2t})_a$- CO_2 emission factor for generating 25% of electricity supplied by candidate CCGT in each month of year t (ton/MWh).

$(COEF_{2t})_b$- CO_2 emission factor for generating 50% of electricity supplied by candidate CCGT in each month of year t (ton/MWh).

$(COEF_{2t})_c$- CO_2 emission factor for generating the remaining 25% of electricity supplied by candidate CCGT in each month of year t (ton/MWh).

COMMEND- Community for Energy, Environment and Development

CP_{m_k} Modular capacity of each of the k plants (MW).

CR- Random Consistency Index

D^*_{ht}- Modelled demand in interval h in year t (MWh).

D_{ht}- Demand in interval h in year t (MWh).

DGGE- Direcção Geral de Geologia e Energia (Directorate General for Geology and Energy)

DSM- Demand Side Management

EC- Emission cost (€/ton).

EEA- European Environment Agency

EFOM- Energy Flow Optimisation Model

EFOM-ENV- Energy Flow Optimisation Model-Environment

EPM- Electricity Planning Model

ERSE- Entidade Reguladora dos Serviços Energetícos (Energy Services Regulatory Authority)

ETSAP- Energy Technology Systems Analysis Programme

EU- European Union

EWEA- European Wind Energy Association

FC- Fixed Cost (€)

F_k- Fuel cost of k type power plants (€/MWh).

F_l- Fuel cost of l type power plants (€/MWh).

$Fuel_x$- Fuel cost of plant x (€/m^3N or €/ton)).

FOM- Fixed Operation and Maintenance

FOM_k- Fixed O&M costs of k type power plants (€/MW-year).

GAMS- General Algebraic Modelling System

GC- Natural gas cost (€/m^3N).

GHG- Greenhouse Gas

h- time intervals in an year t (1, 2, …, 12 months)

HI_{ht}- Hydro inflows at period h of year t (MWh).

HPI- Hydraulic Productivity Index

HPI_{1997}- Hydraulic Productivity Index for the reference year of Directive 200/77/EC

HS_j - Number of hours of hourly step j

i- annual discount rate

IAEA- International Atomic Energy Agency

IEA- International Energy Agency

IEPM- Integrated Electricity Planning Model

I_k- Investment cost of k type power plants (€/MW)

IQR- Interquartil range

$IP_{k=3a,t}$- Total installed power of the candidate onshore wind power plants in year t (MW).

$IP_{k=3b,t}$- Total installed power of the candidate offshore wind power plants in year t (MW).

IP_{kt}- Total installed power of the k type power plants in year t

IP_{lt} - Installed power of l type power plants in year t (MW)

$IP_{NWSRP,t}$- Installed power of non-wind special regime producers (NWSRP), in year t (MW)

IP_W- Installed wind power (MW)

$IP_{OTHER,t}$- Installed power of non-modelled fuel oil plants, in year t (MW)

K- Eigenvector

k- Candidate power plants

k=1	coal	k=2	CCGT
k=3a	wind onshore	k=3b	wind offshore

l- Existing or planned power plants

l=4	coal	l=5	CCGT	l=6	Fueloil
l=7	Large hydro	l=8	SCGT	l=9	wind

LBHG- Installed power of the biggest hydro group (MW)

LBTG- Installed power of the biggest thermal group (MW)

LDC- Load Duration Curve

LL- Load level

$\overline{LL}_{CCGT}$ - Average load level of CCGT during the analysed year

MARKAL- Market Allocation

MAUT- Multi Attribute Utility Theory

MESSAGE- Model of Energy Supply Systems and their General Environmental Impacts

MILP- Mixed integer linear programming

MINLP- Mixed integer non linear programming

m_k- modular capacity of k type power plants

$m_k = 1_2$	330 MW	$m_k = 2_2$	400 MW		
$m_k = 1_1$	300 MW	$m_k = 2_1$	450 MW	$m_k = 3_1$	700 MW

n_k- lifetime of k type power plants.

n- Number of alternatives

NES- National Electricity System

NLEPM- Non LinearElectricity Planning Model

$NMHP_{ht}$- Non-modelled hydro production in interval h of year t (MWh)

NO_x- Nitrogenous oxides

NTC- Net Transfer Capacity

NWSRP- Non Wind Special Regime Producers

Optcr- Optimality tolerance

O&M- Operations and maintenance

P_{kht}- Power output from plant type k in interval h of year t (MW)

PL- Peak Load

P_{lht}- Power output from plant type l in interval h of year t (MW)

PL_t- Peak load in year t (MW).

$P_{sj,x}$ - Average power output of plant x during the hourly step j of week s

$P^*_{NWSRPht}$- Power output from NWSRP excluding fuel and gas cogeneration, in interval h (MW)

$\overline{P}_x$ - Average power output of plant x during the analysed year (MW)

$R_{1,1}$- Initial reserve of the storage hydro power plants, in January 2008 (MWh)

RAC- Reliable Available Capacity

RC- Remaining Capacity

REN- Rede Eléctrica Nacional

RES- Renewable Energy Sources

R_{ht}- Reserve of the storage hydro power plants at the end interval h of year t

RI- Random index

RM_t- Reference Margin in year t

R^2- Determination coefficient of the regression

SBB- Standard Branch and Bound

SC- System Capacity

SFC- Specific Fuel Consumption

SFC_{2t}- Specific gas consumption of candidate CCGT in year t(m^3N/MWh)

SFC_{5t}- Specific gas consumption of existing CCGT in year t (m^3N/MWh)

$SFC_{sj,x}$- Specific fuel consumption of power plant x for the hourly step j of week s.

$(SCF_{5t})_a$- Specific gas consumption for generating 25% of electricity supplied by existing CCGT in each month of year t (m^3N/MWh)

$(SCF_{5t})_b$- Specific gas consumption for generating 50% of electricity supplied by existing CCGT in each month of year t (m^3N/MWh)

$(SCF_{5t})_c$- Specific gas consumption for generating the remaining 25% of electricity supplied by existing CCGT in each month of year t (m^3N/MWh)

$(SCF_{2t})_a$- Specific gas consumption for generating 25% of electricity supplied by candidate CCGT in each month of year t (m^3N/MWh)

$(SCF_{2t})_b$- Specific gas consumption for generating 50% of electricity supplied by candidate CCGT in each month of year t (m^3N/MWh)

$(SCF_{2t})_c$- Specific gas consumption for generating the remaining 25% of electricity by candidate CCGT in each month of year t (m^3N/MWh)

SCGT- Single Cycle Gas Turbine

SCPC- Super Critical Cycle Pulverised Coal

SO_2- Sulphur dioxide

SRP- Special Regime Production/Producers

t - planning period in years (1, 2, …, 10 years)

toe- tonne of oil equivalent

UC- Unavailable Capacity

UCTE- Union for the Co-ordination of Transmission of Electricity

UNCSD - United Nations Commission on Sustainable Development

UNDP-United Nations Development Program

UNFCCC - United Nations Framework Convention on Climate Change

VOM_x- Average variable O&M costs of power plant x

VC- Variable Cost (€)

VOM_k- Variable O&M costs of k type power plants (€/MWh)

VOM_l- Variable O&M costs of l type power plants (€/MWh)

W_{coal}-Normalised weight of the coal solution

W_{gas}- Normalised weight of the gas solution

W_{wind}- Normalised weight of the wind solution

W1- Low growth wind scenario

W2- Moderate growth wind scenario

W3- Reference growth wind scenario

W4- High growth wind scenario

WCD-World Commission on Dams

Z- Identity matrix

ε- Allowable levels of a constraint

$\theta_{m_k t}$ - Total number of m_k modules of candidate power plants in year t

λ- Eigenvalue

Δ_h- Length of the interval h (number of days in a month×24 h)

φ_{kh}- Availability factor of k type power plants, in interval h

φ_{lh}- Availability factor of l type power plants, in interval h

χ_H- Non usable large hydro capacity under a dry regime (%)

χ_{NWSRP}- Non usable NWSRP capacity (%)

χ_W- Non usable wind capacity (%)

χ_W- Non usable hydro capacity (%).

Definitions

Capacity credit of wind- represents the amount of conventional generation that can be displaced by wind generation, without affecting the reliability of the total system.

CO_2 abatement of wind power- reduction of CO_2 emissions per unit of electricity produced from wind (ton/MWh). This value depends on what production type and fuel is replaced when wind power is produced.

CO_2 allowance- Represents the right to emit one tonne of carbon dioxide equivalent during a specified period. These allowances are issued to carbon producers companies according to the National allocation schemes and may be transferred between companies.

Electricity demand (or consumption) of a region- Corresponds to: final consumer's electricity consumption + the distribution and transmissions losses+ autoconsumption. It is also the same as the: total electricity production + electricty imports – electricity exports.

Electricity intensity of the economy- total electricity consumption per unit of Gross Domestic Product

Energy intensity of the economy- total energy consumption per unit of Gross Domestic Product.

EU-15- European Union member states: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom.

EU-25- European Union member states: Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, United Kingdom.

EU-27- European Union member states: Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom.

External dependency of the electricity generation and supply sector- proportion of energy used in meeting the demand for electricity that comes from imports (including electricity imports) $\left(\frac{\text{Electricity generated from imported fuels} + \text{Imported electricity}}{\text{Total electricity used in the country}}\right)$.

External energy dependency of the country- percentage share of primary energy used that come from imports $\left(\frac{\text{Total energy imported}}{\text{Total energy used in the country}}\right)$.

Externalities- Unpriced costs and benefits which arise when the social or economic activities of one group of people have an impact on another.

Hydraulic Productivity Index (HPI)- ratio between the hydropower production during a time period and the hydropower production that would be expected for the same period under average hydro conditions.

Load duration curve (LDC)- curve presenting the number of hours over the course of a time period during which the load exceeds a certain value.

Load factor- measure of the electricity that a power plant produces during a certain period compare to the maximum possible production level over the same period[1].

Load level- measure of the energy that the unit produces during a certain period compare to the maximum possible production that could be obtained if the unit would be operating at full load whenever it is called to the system during the same period[2].

Merit order- Ordered list of electricity generators established according to their prices or variable costs for electricity production.

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[1] For an year period (8760h): Load factor= $\frac{\text{Energy produced by unit k during year t}}{\text{Power of unit k} \times \text{8760 h}}$

[2] For an year period (8760h): Load level= $\frac{\text{Energy produced by unit k during year t}}{\text{Power of unit k} \times \text{number of effective operating hours in year t}}$

Modelled electricity production/demand- Calculated as the difference between total electricity consumption and the non modelled electricity production.

Non modelled electricity production- Electricity production not included in the optimisation process, namely: NWSRP, run of river hydro generation, share of the hydro storage committed to non electricity usages and Tunes, Carregado and Barreiro production.

Non-usable capacity- Capacity that cannot be scheduled due to reasons like the temporary shortage of primary energy sources (hydroelectric plants, wind plants), power plants with multiple functions, in which the generating capacity is reduced in favour of other functions (cogeneration, irrigation, etc.), reserve power plants which are only scheduled under exceptional circumstances and unavailability due to cooling-water restrictions.

Peak load (peak demand)- maximum power absorbed by all the installations connected to the transmission or distribution system during the year.

Reliable available capacity- available generation after allowing for the unavailable capacity.

Remaining Capacity- capacity that the system needs to cover exceptional demand variation and longer term unplanned outages of power plants. Calculated by the difference between Reliable Available Capacity and Peak Load.

Renewable energy sources (RES)- Energy resources that are replenished: geothermal, solar, wind, tide, wave, hydropower, biomass and biofuels.

Reserve margin- ratio computed as $\dfrac{\text{Installed power} + \text{Importation capacity - Peak demand}}{\text{Peak demand}}$ for each year.

Reference margin- ratio computed as $\dfrac{\text{Reliable available capacity - Peak load}}{\text{System capacity}}$ for each year.

specific CO2 emission factor (COEF)- amount of CO2 released per unit of electricity produced (ton /MWh).

Specific fuel consumption (SFC)- amount of fuel consumed in a power plant per unit of electricity produced (m3N/MWh for CCGT and ton/MWh for coal and fueloil).

Special regime producers (SRP)- Includes the small hydro generation, the production from other non hydro renewable sources and the cogeneration[3].

Stakeholder- Agency, group of people, or individuals that are affected by, or have an interest in the decision under analysis.

System capacity- maximum power that a certain electricity system can produce.

Unavailable capacity- non usable capacity, overhauls, outages and system reserve.

Value of wind power- cost reduction per unit of electricity produced from wind (€/MWh). This value depends on what production type and fuel is replaced when wind power is produced.

[3] Cogeneration or combined heat and power, is the simultaneous production of electricity and useful heat from the same fuel or energy.

CHAPTER I

INTRODUCTION

This chapter starts by describing the context of the thesis. The objectives of the research are then enumerated and the methodology used for the research is summarised. A description of the chapters is presented at the end.

I.1 Scope

There exists a strong link between energy, environment and sustainable development. Energy is a key factor for the development of economies. It has a direct impact on the economic performance of companies and it is also a driving force for social welfare. It is fundamental to have a good balance between the use of energy for development and environment preservation, as excessive use may lead to negative ecological impacts. Greenhouse gas emissions represent a particularly relevant global problem that has been catching governments' attention for more than a decade. No less important are the local and regional environmental impacts, related to the emissions from fossil fuel combustion, the deforestation, or the loss of fauna and flora. In addition, although energy projects can create important local development opportunities generating positive incomes for local communities, these projects frequently also have to face strong social opposition.

In 1987 the Brundtland Report (World Commission on Environment and Development, 1987) presented what became a widely recognised definition of sustainable development "Sustainable development is development which meets the needs of the present without compromising the ability of future generations to meet their own needs". Much of the sustainable development references focus on environmental sustainability. However, the Brundtland Report made clear the need to expand the sustainable development concept beyond ecological concerns and fully recognise and integrate the social dimensions of sustainability. The sustainable development concept is now generally accepted as a process of change that balances the protection of the environment with economic productivity and the provision of social welfare. The environmental dimension of sustainable development relates to the need to protect natural resources, recognising that human welfare depends on the availability and use of these resources. As for the economic concept, it focuses on the need to maximise income and the overall economic wellbeing. Finally, the social dimension reflects the need to ensure equitable social progress and overall social welfare.

Ensuring a sustainable society for future generations rests, to a large extent, on designing and implementing a sustainable energy sector. According to Hepbasli (2007), "a sustainable energy system may be regarded as a cost-efficient, reliable, and environmentally friendly energy system that effectively utilizes local resources and networks." In line with this definition, Jefferson (2006) provided the four key elements of sustainable energy: sufficient growth of energy supplies to meet human needs, energy efficiency and conservation measures, addressing public health and safety issues and the protection of the biosphere. The reduction in the use of fossil fuels, the increase in energy efficiency and the promotion of the exploitation of renewable energy sources (RES) are then, fundamental measures to meet the goal of sustainable energy development. These measures were highlighted in the Kyoto protocol document[4], and reinforced in the European Commission policy documents for the energy sector (Commission of the European Communities, 2007a).

Energy consumption is growing strongly across the world. The electricity subsector is advancing even at a higher rate, with the forecasts for the sector indicating that no stagnation or decline of consumption can be expected for the next 20 years.

According to the Energy Information Administration (2007) forecasts, world electricity generation is expected to nearly double from 2004 to 2030. Natural gas is the fastest-growing energy source for electricity generation worldwide. Nevertheless, coal continues to provide the largest share of the energy used for electric power production and is expected to remain so until at least 2030. As for RES in electricity production, these sources are projected to increase in absolute values, mostly due to environmental reasons. However, this projection also indicates that RES share in percentage terms, may fall slightly as growth in the consumption of both coal and natural gas, in the electricity generation sector worldwide, exceeds the expected growth in renewable energy consumption.

At the European level, electricity generation is projected to grow slowly in comparison to world projections, as a result of slow population growth and the already well-established electricity markets in Europe (Energy Information Administration, 2007). The power generation structure in Europe is expected to change significantly in favour of renewables and natural gas, while nuclear and solid fuels will loose market shares. The growth of wind power is expected to be particularly high. In total, wind energy in 2030 should provide twenty times as much electricity as was available from this source in 2000. In 2030, wind power is expected to produce more electricity than hydro in the European Union (EU)

[4] http://unfccc.int/essential_background/kyoto_protocol/items/1678.php

region (European Commission, 2006a).

In Portugal, the electricity production sector is the largest consumer of primary energy. In 2005, about 34% of the primary energy consumption was related to electricity production activities followed by the transportation sector, which is the largest consumer of oil. According to the Rede Eléctrica Nacional (REN, 2005) forecasts, electricity consumption in Portugal is expected to grow at a yearly rate close to 4.4% during the next decade, a value much higher than the average projections for the EU. The REN projections indicate that considerable changes in the Portuguese electricity generation structure are expected, with a significant move towards RES, mainly supported by strong investments in wind technology.

The rising trend of electricity demand, the volatility of fossil fuel prices, the external energy dependency and environmental concerns have been major drivers for an increasing interest in RES. The integration of renewable resources is expected to play a major role for the attainment of the sustainable development goal, and it is a key element of the European and Portuguese strategies for the energy sector, as represented in Figure 1.1.

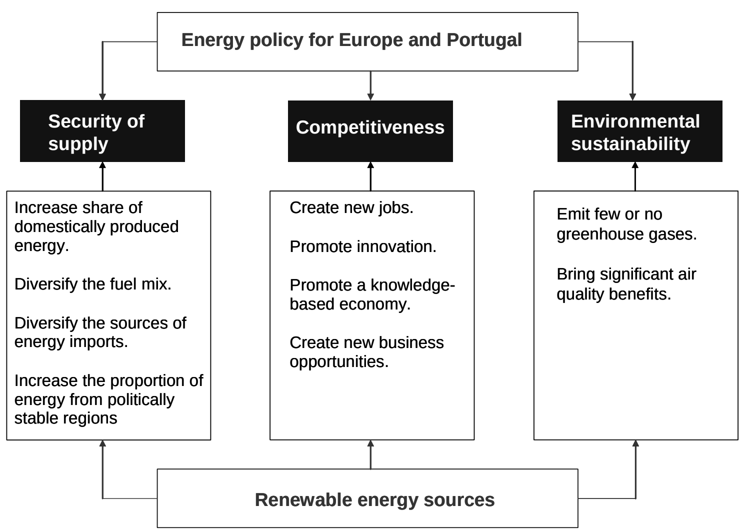

Figure 1.1- Contribution of the RES to European and Portuguese objectives for the energy sector. Source: Own elaboration of the Commission of the European Communities (2007a) report.

The cost impact of an increasing reliance on RES is not yet clear, depending heavily on the future fossil fuel prices and on the carbon emissions prices. However, it seems that the gap between the cost of electricity generation from RES and the cost of generation from conventional thermal power plants is narrowing. Studies like Moran and Sherrington

(2007) or Owen (2006) indicate that technologies like wind power are increasingly becoming ever more competitive than with more traditional electricity generation ones.

The creation of clear energy strategies merging cost effectiveness with environmental and social issues is the main challenge for energy planners. Cost oriented approaches, where the monetary assessment is the only basis for the decision making, are no longer an option, and information on the ecological and social impacts of the possible energy plans, needs to be combined with traditional economic monetary indicators. The existence of different perspectives and values must also be acknowledged and fully incorporated in the planning process, avoiding centralised decisions based on restricted judgements. The evolution of the market conditions and the increasing concerns with sustainable development have brought about profound changes in the approach to the energy decision process and to the priority assigned to each objective, during the energy planning process. Sustainable energy planning should now be seen as a multidisciplinary process, where the economic, environmental and social impacts must be taken into consideration, at local and global levels, and where the participatory approaches can bring considerable benefits.

Electricity power planning faces particular complex challenges:

- The decision making process must be based on an incremental power planning approach. The planning process requires a full understanding of the existing electricity system, of the operational procedures as well as, of the characterisation of possible new plants. Future energy strategies and decisions on the integration of new power plants will be strongly influenced by the currently existing power system.

- Government policies for the energy sector highly constrain electricity planning. Aspects such as the Kyoto protocol, the European Directives focusing on the promotion of electricity from RES (Directive 2001/77/EC) and the limitation of emissions from large combustion plans (Directive 2001/807/EC), must be taken into consideration during the planning process.

- The planning process relies on uncertain forecasts for the planning period: the fossil fuel markets are unstable, technology development constantly creates new options, the demand growth is difficult to predict even more so in competitive electricity markets and government regulations and policies for the sector change frequently.

- Depending on the characteristics of the power system under analysis, the integration of technologies of variable output, like wind power, has a significant impact on system management and on the reserve requirements. The computation of the cost and emissions of the system is not a straightforward process and large amounts of wind can influence significantly the operating conditions of the thermal power plants, with consequent effects on their efficiency. Thus, long term electricity planning requires the incorporation of the operation of the entire system.

- Environmental impacts of electricity generation activities become increasingly critical. The need to control atmospheric emissions of greenhouse and other gases and substances requires the full evaluation of the environmental characteristics of each electricity generation technology, and the inclusion of environmental objectives in the electricity planning process.

- The complexity of the problem increases further due to the desirable inclusion of a number of objectives, some of which may be unquantifiable and/or subjectively valued, thus making energy planning decisions prone to some degree of controversy. Renewable energy projects and in particular wind power plants, frequently have to face local opposition and the spread of these renewable technologies may be slowed by low social acceptability. The electricity planning process needs to rely on a formal approach to the assessment of social acceptability of the generation mix.

Sustainable long range electricity planning involves tradeoffs between multiple goals and, rationally, the multiple attributes of each competing and acceptable electricity generation technology or portfolio, in terms of the attainment of goals, must be assessed. Integrated resource planning should seek to identify the mix of resources that can best meet the future electricity needs of consumers, the economy, the environment and society.

Designing an electricity power planning model requires more than a straightforward selection and application of existing models. Although the review of scientific literature played a fundamental role in all steps of the research conducted here, the planning process also requires a detailed characterisation of the power system under analysis. In addition, the management of the electricity system is highly complex and based on rules defined according to the technical characteristics of each particular system and the associated legal framework. Thus, researchers although backed up by a strong literature review, should not overlook the benefits of conducting meetings and interviews with electricity experts and managers of the system, whose experience can bring invaluable contributions to the planning models.

Figure 1.2 presents the overall perspective of the main steps required to develop a decision framework for electricity planners, with the goal of obtaining feasible and sustainable electricity power plans. This figure may also be seen as the general guide to the research conducted and presented in this thesis.

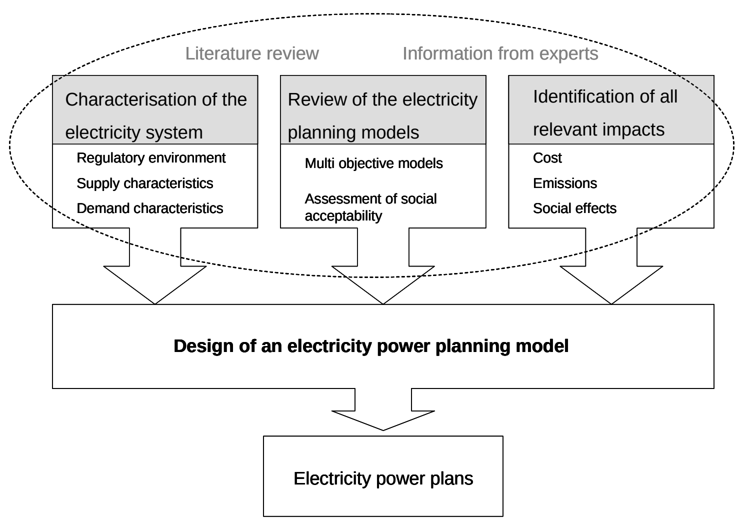

Figure 1.2- Guidelines for sustainable electricity power planning.

The general inputs to the model design at a generic level are:

- The technical, legal and demand characteristics of the system. The electricity planner must start out the planning process with the existing generation mix and modify this mix over time, having in mind not only the need to meet the forecasted demand but also the regulatory constraints, such as minimal RES share, security of supply levels or external dependency limits.

- The existing electricity planning models that allow for the integration of more than one objective and possible approaches to the assessment of social acceptability. These models may be based on optimisation procedures, multicriteria tools and participative approaches.
- The economic, environmental and social impacts associated with the electricity generation technologies. Local, regional and global impacts should be included in the analysis.

By merging this information, an electricity power planning model is developed, which is adapted to the specific characteristic of the system and based on scientific evidence and on empirical data[5]. The final output of the models is a set of feasible optimal electricity power plans integrating economic, environmental and social concerns. These plans, along with a full description of their expected impacts may then be presented to the decision maker who will have the final task of choosing the best optimal plan.

I.2 Objectives of the research

The main objective of the research is to develop an integrated electricity planning model to support decision making on future electricity generation strategies and to apply it to the Portuguese electricity system. The specific objectives can be summarised as follows:

1. To structure the electricity planning process by initially identifying and analysing: i) the most relevant technologies at present and future prospects; ii) the most important impacts associated with each electricity generation technology; iii) the different approaches and models used in the planning process.

2. To present an integrated multidimensional electricity planning model incorporating: i) relevant energy, economic, environmental, and technical data; ii) evaluation criteria addressing the three dimensions of sustainable development: economic, environmental and social.

3. To implement the proposed model for long term sustainable electricity planning in

[5] The network infrastructural development possibilities were not take into account in this study due to the lack of available data. However, for some systems they may represent also an important cost to include in the electricity planning process.

Portugal.

4. To propose a general framework to support sustainable electricity planning: flexible enough to be applied to different systems but also robust enough to deal with the complexity and multidimensionality of the system under analysis.

The overall model must recognise the multiple and conflicting objectives involved in energy decisions, dealing with the large economic and environmental costs involved and also eliciting the social values and priorities. The process must combine demand forecasting with investment planning, assessing whether incremental demand should be met through existing power plants or through the addition of new generation capacity.

I.3 Methodology

During the research, a literature search was undertaken from primary, secondary and tertiary sources comprising books, websites, reports from companies operating in the sector and public organisations and papers published in scientific journals. The objective was to gain an understanding of the problem and of the possible approaches, forming the theoretical basis of the work.

The work also included an extensive data collection, which focused mainly on the Portuguese electricity sector. Statistical information was obtained from the reports published by the companies operating in the sector and data published by the Portuguese Directorate General for Geology and Energy (DGGE). The technical characteristics of the existing power plants were obtained from official reports of the companies operating them. The expected characteristics of future power plants came from works published by organisations such as the International Energy Agency (for example IEA/NEA, 2005).

Collaboration with companies in the sector was an essential element of the research, both through direct data collection and through their involvement in the running of the models. Particularly remarkable was the interest shown by REN and their effective participation in the study. It should, however be underlined that achieving the collaboration of the companies was a complex and long procedure. Many of the contacted companies showed little or even no interest in collaborating, justifying this approach with the need to protect private commercial information now that they are operating in the free electricity market in Portugal.

The process of data collection involved a large number of interviews with experts based in private companies, universities and public organisations, providing information, advice, guidance and giving their insights on the subject. The information collected helped in the identification of the most important criteria to be taken into consideration in the electricity planning process and in the formulation of the mathematical models applied to the specific Portuguese case.

The models were based on the combination of two fundamental methods: i) multiobjective optimisation and ii) participatory techniques. The mathematical formulation resulted in mixed integer linear and non linear models. The models were then implemented in a computational language and solved using commercial/academic solvers selected according to the models. The participative process combined the Delphi process with the Analytic Hierarchy Process (AHP) for the collection of information and analysis of questionnaire responses. The application to the Portuguese case involved the participation of a selected number of experts who agreed to participate in the research as a pilot group. The overall proposed methodology integrated economic, environmental and social aspects through the combination of multiobjective programming models with models dealing with discrete scenarios, resulting in a new decision aid framework for electricity power planners.

I.4 Organisation of the dissertation

The work was conducted according to the objectives outlined and is organised as follows:

Incremental electricity planning requires the full characterisation of the electricity system under analysis. Chapter II addresses this characterisation and analyses the situation of electricity production in Portugal. The market organisation is presented along with the demand evolution, the role of RES for electricity generation, and future prospects. Particular attention is given to the wind power sector due to its increasing importance, focusing on issues such as the additional reserve requirements and the importance of the interconnection capacity. The Portuguese case is briefly compared to the Danish, German and Spanish positions. During this phase of the research, the generation technologies presently operating in the Portuguese electricity system were identified along with the expected development of the sector according to the REN (2005) forecast. Chapter II is mainly based on information collected from official reports, legal texts and documents published by companies operating within the sector.

Chapters III and IV aim to bring a theoretical background to the thesis, by making reference to previous studies on electricity planning and different approaches used by several authors. The integration of electricity generation using RES into the grid is discussed. These chapters consist of a bibliographical review mostly based on scientific papers and on some works published by international organisations or institutions, such as the European Commission or the World Bank. Referring to Figure 1.2, these chapters provide the required additional information for the electricity planning process: a review of electricity planning models and the identification of the impacts of different electricity generation technologies.

Chapter III consists of a survey of different energy planning approaches. The chapter starts by addressing the relationship between energy and sustainable development and dicusses the role of RES. A review of the energy planning models is then presented, describing past works based on optimisation procedures, multicriteria tools and cost benefit analysis. Questions such as the monetisation of external costs and the public involvement in energy decision making are addressed. Recent works focusing on the integration of RES in energy planning are analysed, demonstrating the importance of a proper assessment of the impacts of each generation technology or electricity plan.

In Chapter IV the main impacts associated with each electricity generation technology are described. The close relationship between energy production and environmental damage is discussed in the light of international agreements such as the Kyoto protocol and the EU renewables Directive 2001/77/EC. The link between energy and the worldwide global warming effect is highlighted, demonstrating the close relationship between energy consumption based on fossil fuels and CO_2 emissions. The local and regional impacts of electricity generation activities are also analysed, focusing on aspects such as noise, deforestation, habitat destruction and socioeconomic effects. This chapter closes with a description of the most frequently reported problems for wind plants, including the impacts on birds and wildlife, the visual impact and wind turbine noise. The integration of wind power into the grid as a generation technology of variable output is also analysed, discussing the impact on the generation cost, the impact on the reduction of the emissions and the public attitude towards wind power. At the end of Chapter IV a general approach to the sustainable electricity planning problem is presented, based on the information collected in the literature research and introducing the following chapters, which are the core of the research conducted.

Chapter V and VI consist of the application of the proposed general approach to the specific case of Portugal. Referring to Figure 1.2, this corresponds to the phase of the design of an electricity power planning model for a particular system.

Chapter V describes the formulation of multiobjective mathematical models for the incremental electricity planning in Portugal for a ten years period (2008-2017), departing from the 2006 situation. Their formulation involved: data collection from reports, legal texts and documents published by companies operating within the sector; the translation of the technical and legal requirements into mathematical functions (constraints); and the formulation of economic and environmental objectives which are also translated into mathematical functionals. This stage of the research, greatly benefited from information collected in meetings and interviews with electricity experts and with managers of the Portuguese electricity system.

The models resulted in mixed integer optimisation problems, both linear and nonlinear. The linear model assumes average operating conditions for all power plants and no significant impacts on the system operation are assigned to wind power. On the other hand, the non linear model takes into consideration the impacts on cost and CO_2 emissions from increasing levels of wind power in the system, based on an experimentally derived mathematical relationship between the installed wind power and the expected efficiency of the thermal power plants. Both models were written in GAMS codes for the optimisation process.

The final results are a set of optimal electricity power plans for each model, detailing: the electricity generation schedule for the next ten years, the monthly plans for electricity production, the yearly plans for generating capacity expansion, the total cost and the level of CO_2 emissions. The sensitivity of the results to changes in variables such as CO_2 market

cost, interest rate and fuel costs was also analysed.
The chapter closes with a discussion of the models and their results.

Chapter VI integrates the results obtained from the optimisation models with the assessment of the social impacts of the electricity generation technologies. The process started with the identification of the relevant social impacts of each electricity generation technology included in the optimal plans. This information was obtained from a literature survey complemented by semi-structured interviews with experts of the energy sector. A group of academic experts was then selected to participate as a pilot group on a process combining Delphi and AHP methods, for the pairwise comparison of the electricity generation technologies against the social criteria. A social index was then derived and assigned to each technology. The final output of the social analysis is an Average Social Index of each possible generation mix. The chapter closes with a discussion of the analysis conducted, presenting the main achievements and limitations, emphasising the need for future research.

Based on the research conducted, Chapter VII proposes the Integrated Electricity Planning Model (IEPM). A comprehensive methodology for dealing with long term electricity planning is presented, formulating the necessary guidelines to combine economic, environmental and social objectives in the process.

In Chapter VIII the conclusions of the thesis are presented. The thesis background and its main results are described along with the limitations of the models and a number of possible research questions for the future are outlined.

Finally, the references are included along with a set of annexes, presenting: data used, GAMS codes, results of different models, Delphi questionnaires and statistical analysis of the responses.

CHAPTER II

THE ELECTRICITY SECTOR IN PORTUGAL

Electricity consumption is growing very rapidly in Portugal and the role of renewable energy technology is becoming increasingly relevant. In respect to renewable energy sources, the large hydro sector will maintain a dominant position for several years, but wind power is expected to rapidly gain importance. The intensive use of wind energy combined with the increased demands for electricity will give rise to considerable changes in future electricity generation mix structure in Portugal.

II.1 Introduction[6]

Portugal is strongly dependent on external energy sources, in particular oil. In 2005, 87% of the primary energy came from imports, and oil represented about 59% of the primary energy consumed. The main national resources come from renewable energy sources (RES), especially the hydro sector for electricity production. Thus, the renewable energy sector has a fundamental role for the reduction of the external energy dependency, actively contributing to increasing the security of supply. Figure 2.1 presents the energy balance for Portugal in 2005.

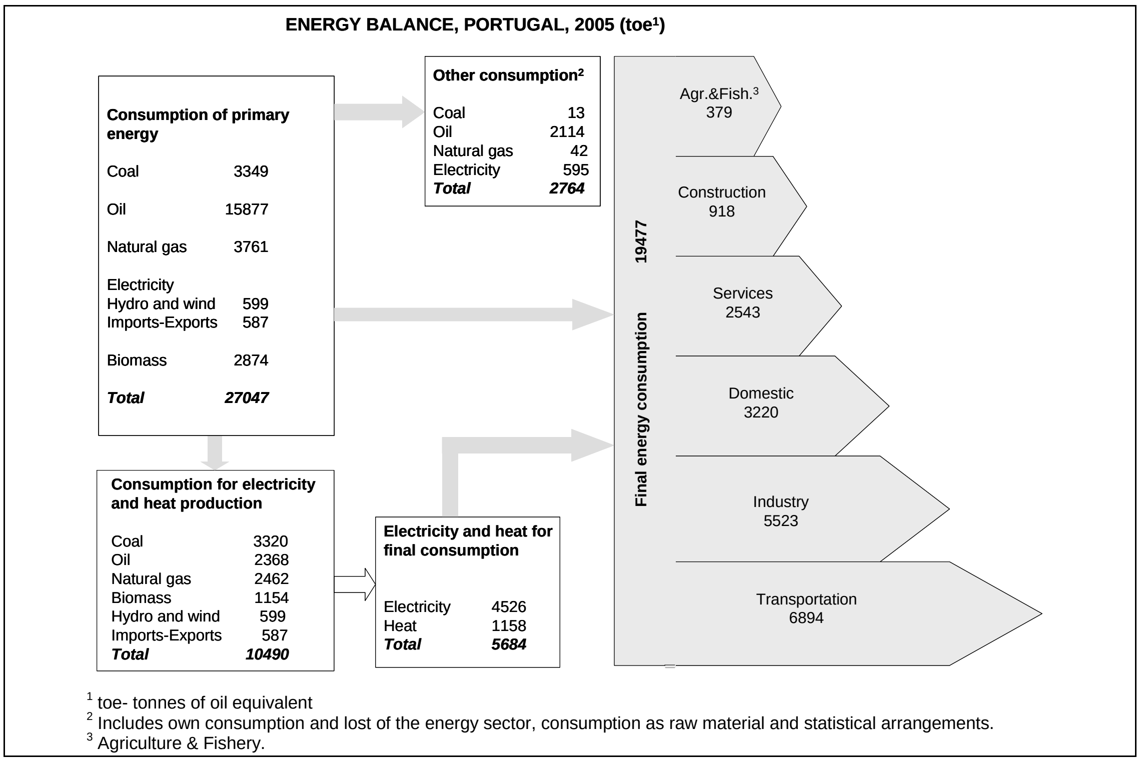

Figure 2.1- Energy balance for Portugal in 2005. Source: Own elaboration of data drawn from DGGE site (www.dgge.pt).

The electricity and heat production activities accounted for more than 38% of the total primary energy consumption in 2005 and 83% of electricity consumed in Portugal came from imported fuels and from electricity imports from Spain. Electricity production was then the largest consumer of primary energy and also the largest consumer of imported energy resources. However, 2005 was an extremely dry year resulting in the lowest hydro power production of the last ten years and a large increase in energy importations. In

[6] The study focuses on inland Portugal and does not include Azores and Madeira islands. Part of the information presented in this chapter was published in a previous paper from the authors (Ferreira et al., 2007a).

comparison, 2003, a wet year, the external energy dependency[7] of the country was 83% and the external dependency of the electricity generation sector[8] was 72%[9]. These values demonstrate the importance of the hydro sector but at the same time show that even under the best conditions, the external energy dependency of the country remains very high.

According to the Portuguese 2007 submission to the UN Framework Convention on Climate Change (European Environment Agency, 2007), in 2005 about 31% of National Carbon Dioxide (CO_2) emissions were due to public electricity and heat production, emphasising the need to evaluate the use and integration of low carbon emissions technologies in the electricity system.

In 2005, Resolution 169/2005 established the present energy strategy for Portugal, where the role of renewable energy was highlighted. The Portuguese government, based this policy for the energy sector on three strategic concerns: assuring the security of supply, stimulating sustainable development and promoting national competitiveness. To achieve these objectives, the government proposed measures focused on:

- Increasing renewable energy shares, in particular wind energy.
- Reducing the fossil fuel usage and promoting more efficient technologies.
- Proceed with the liberalisation of the electricity and natural gas sectors.

At the European level, Directive 2001/77/EC for the promotion of electricity generation from RES was published in September 2001. In this document, an European indicative target was set: 12% of gross domestic energy consumption by 2010 produced from RES. It also sets National indicative targets for each European Union (EU) country, consistent with this overall indicative target and in particular with the objective of reaching 22.1% share of electricity produced by RES in total Community consumption, by 2010. As for Portugal, the share of electricity produced by RES was about 38.5% of the gross electricity consumption in 1997. The directive sets a target of 39% in 2010, in recognition of the

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[7] The external energy dependency of the country represents the percentage share of primary energy used that come from imports, computed as $\dfrac{\text{Total energy imported}}{\text{Total energy used in the country}}$.

[8] The external dependency of the electricity generation sector represents proportion of energy used in meeting the demand for electricity that comes from imports (including electricity imports), computed as $\dfrac{\text{Electricity generated from imported fuels} + \text{Imported electricity}}{\text{Total electricity used in the country}}$.

[9] Own calculations based on DGGE data for 2003, drawn from DGGE site.

expected growth of electricity consumption for the following years. This target assumes for Portugal that (Directive 2001/77 /EC, annex):

"— it will be possible to continue the national electricity plan, building new hydro capacity higher than 10 MW,

— other renewable capacity, only possible with financial state aid, will increase at an annual rate eight times higher than has occurred recently.

These assumptions imply that new capacity for producing electricity from renewable sources, excluding large hydro, will increase at a rate twice as high as the rate of increase of gross national electricity consumption."

The wind electricity generation sector is essential for the attainment of the European renewable objectives. According to the EU forecasts, the large hydropower will maintain its dominant position in RES for electricity generation for the near future. However, the use of wind energy will continue expanding and, in 2020 the wind electricity generation capacity will overcome the hydro sector in the EU-27[10] (European Commission, 2006a). During the period 1993 to 2006, the world wind power installed capacity increased from 2900 MW to 72628 MW. In the EU-25[11], the total installed capacity reached 48531 MW, mostly concentrated in Germany, Spain and Denmark (EuroObserv'ER, 2007). According to the EWEA (European Wind Energy Association) forecasts, it is feasible for wind power to supply 12% of the world's electricity demand by 2020 (EWEA, Greenpeace, 2005). At the European Union level, the contribution of wind energy in electricity power generation is expected to grow over time, reaching 7.6% of total electricity production in 2020 and about 10% in 2030 (European Commission, 2006a).

Portugal is no exception to the increase of wind energy for electricity generation, and the wind sector is growing rapidly. EurObserv'ER (2007) even classified the 2006 growth of the Portuguese wind market as "spectacular", with more than 600 MW installed during the year corresponding to a 61% increase over the installed capacity at the beginning of the year. If the government objectives for wind energy for electricity generation are met, by

[10] Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom

[11] Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, United Kingdom

2010 the wind power share may reach values comparable to the present Danish situation (24% of the total installed capacity) and higher than in Germany (17% of the total installed capacity) or Spain (14% of the total installed capacity)[12].

In the next sections an overview of the electricity system in Portugal is given. After this introduction, the present organisation of the Portuguese electricity system is presented along with the main agents of the market (Section II.2). In section II.3, the electricity demand trends are analysed, focusing on electricity consumption forecasts and on the evolution of the energy intensity of the economy. Section II.4 describes the Portuguese electricity generation system, presenting the generation technologies currently operating and its expected structure in the next ten years. The role of the renewable energy technologies for electricity generation is also analysed. Section II.5 details the evolution of the wind power sector and the future prospect of the sector is given. The Portuguese case is compared with other wind power leading countries and key challenges for the accommodation of large wind scenarios on the electricity system, are acknowledged. The chapter closes with some concluding remarks.

II.2 Organisation of the Portuguese electricity system

The organisation of the Portuguese electricity sector was recently redefined by Decree-Law 29/2006[13]. The framework for an integrated National Electric System was outlined, establishing that (ERSE, 2006):

- The activities of generation and supply are to be conducted henceforth on the basis of free competition, following the award of a license.

- Transmission and distribution activities are to be conducted following the awarding of public service concessions.

- Suppliers may freely buy and sell electricity. To this effect, they may access the transmission and distribution grids, against the payment of regulated tariffs.

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[12] Own calculations based on Danish Energy Authority (2007), VDN (2007) and REE (2007) data.

[13] A detailed description of the Portuguese electricity market before Decree-law 29/2006 may be found in a previous paper from the authors Ferreira et al. (2007b).

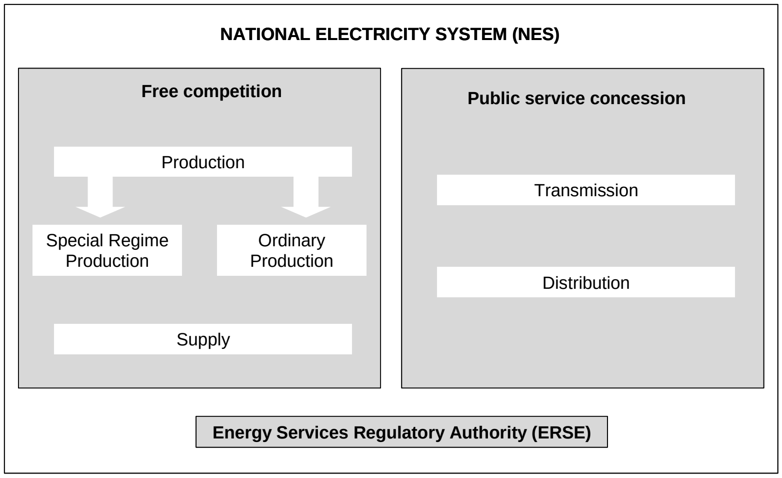


Figure 2.2- National electricity system.

Figure 2.2 represents the general structure of the National Electricity System (NES). The production activities comprise the ordinary production and Special Regime Production (SRP). The SRP include the small hydro generation, the production from other renewable sources and the cogeneration. These producers have priority access to the grid system under the established feed-in tariffs for the licence period. Rede Eléctrica Nacional, SA (REN) presently owns the concession for the transmission activities and EDP Distribuição - Energia, SA owns the concession for medium and high voltage distribution. The transmission system operator is also responsible for the overall technical management of the electricity system. The Energy Services Regulatory Authority (ERSE) regulates the Portuguese energy sector.

II.3 Electricity demand[14] trends

The Portuguese electricity consumption represents only a small share of the global EU consumption (about 1.6% in 2005). The electricity intensity of the economy presents a different pattern from the EU-27 average. At the EU level, there has been a general decline in the electricity intensity of the economy[15]; between 1995 and 2005 this indicator fell almost 4%, from 394 MWh/10^6 € to 379 MWh/10^6 €. However, the Portuguese electricity intensity of the economy is still rising. Between 1995 and 2005, this value increased about 23%, reaching a figure 27% higher than the EU-27 average. The Portuguese electricity intensity of the economy rose from 392 MWh/10^6 €, a value close to the EU-27 average, to

[14] Electricity demand (or consumption) of a region corresponds to: Final consumer's electricity consumption + the distribution and transmissions losses+ autoconsumption + electricity imports – electricity exports. It is also the same as the total electricity production + electricty imports – electricity exports.
[15] This indicator is the ratio between consumption of electricity and the Gross Domestic Product calculated for a calendar year.

483 MWh/10^6 €.

Figure 2.3 illustrates the evolution of the electricity intensity along with the evolution of the energy intensity of the economy for the EU-27 and Portugal. The electricity intensity is computed from the ratio between total electricity consumption and the Gross Domestic Product at constant 1995 prices (GDP_{1995}), measured in GWh/ Million €. The energy intensity is computed from the ratio between the total energy consumption and the Gross Domestic Product at constant 1995 prices (GDP_{1995}), measured in toe[16]/ Million €.

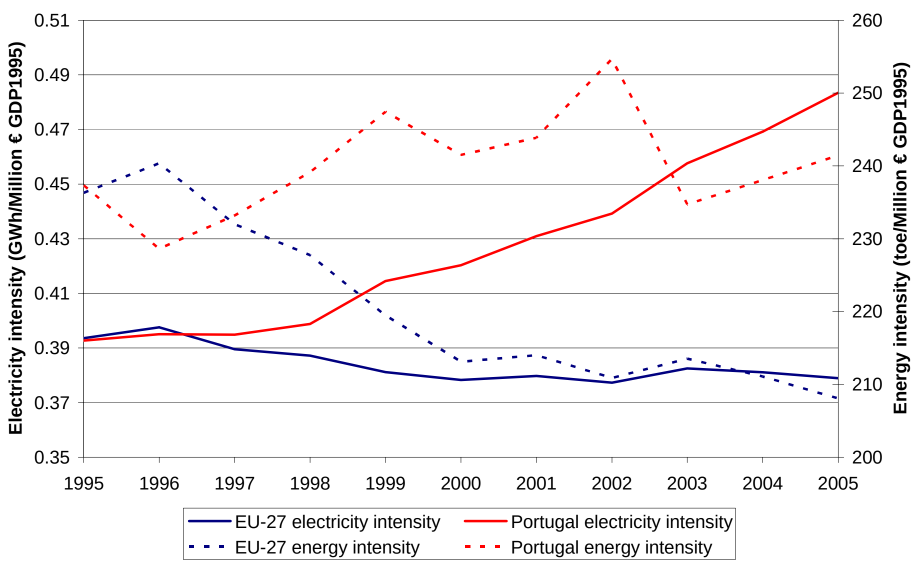


Figure 2.3- Electricity and energy intensity of the economy, Portugal and EU-27, 1995-2005. Souce: Own elaboration of Eurostat data.

The energy intensity of the EU economy presented a clear decreasing trend and during the analysed period the values fell by 12%, from 236 toe/10^6 € in 1995 to 208 toe/10^6 € in 2005.

The improvement of both the electricity and energy intensity of the economy at the EU level may be explained by technological progress, induced by economic growth and by modernisation of installations in all sectors of the economy, thereby improving the efficiency of the energy system. Also, the restructuring of the sectoral pattern of economic growth, which gradually shifts away from traditional energy-intensive products and concentrates on high value added activities, contributes for the reduction of the energy

[16] toe- tonne of oil equivalent.

intensity (European Commission, 2006a).

The Portuguese energy intensity although showing a general increasing trend, presents an unstable pattern. Between 1995 and 2005, this indicator increased from 237 toe/10^6 € to 241 toe/10^6 €. The energy intensity of the Portuguese economy increased slower than the electricity intensity, reflecting greater efficiency of the energy system transformations and less efficiency on energy utilisation among the final consumers.

According to REN (2005) forecasts, electricity consumption in Portugal will continue to rise at an average yearly rate close to 4.4% in the period 2006 to 2016, reaching 82070 GWh in 2016. European Commission (2006a) forecasts however, indicate that between 2000 and 2010 this annual increase of the Portuguese electricity consumption will be 3.8%, after 2010 there will be a slowing down of the electricity consumption increase and the annual change will be 2.9% until 2020 and 1.3% between 2020 and 2030. In addition, the same forecasts predict that improvements to the energy intensity may be expected for the next decades both for Portugal and EU-27.

II.4 The Portuguese electricity generation system

At present, the Portuguese electricity generating system is basically a mixed hydrothermal system. The total installed power reached in 2006 about 13619 MW, distributed between thermal power plants (coal, fuel oil, natural gas and gas oil), hydro power plants and SRP, as presented in Table 2.1. In addition, the Portuguese system is interconnected with Spain and the available capacity for commercial electricity transactions is 800 MW. In 2006, the total electricity consumption reached 52764 GWh (DGGE, 2007).

Table 2.1- Distribution of installed power and electricity production in mainland Portugal, 2006. Source: REN(2007)

	Installed power (MW)	**Electricity production (GWh)**[1]
Thermal power plants	5896 (43%)	25478 (57%)
Large hydro power plants	4582 (34%)	10204 (23%)
Special regime producers	3141 (23%)	8752 (20%)
Total	13619 (100%)	44434 (100%)

[1] Injected in the public grid.

A detailed description of the present and future Portuguese electricity generating system may be found in Annex 1. The contribution of each electricity generation technology to cover the electricity demand is given in Figure 2.4 for a typical winter day and in Figure 2.5 for a typical summer day.

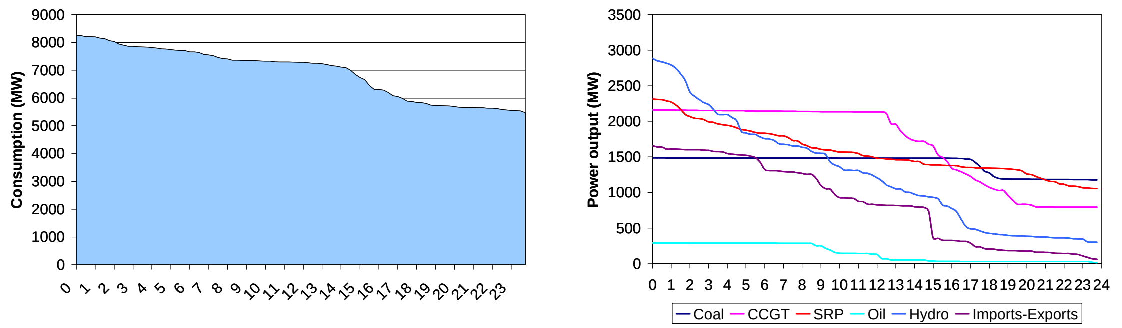


Figure 2.4- LDC for a winter day (08.02.2007). Source: Own elaboration of data collected from REN site in June 2007.

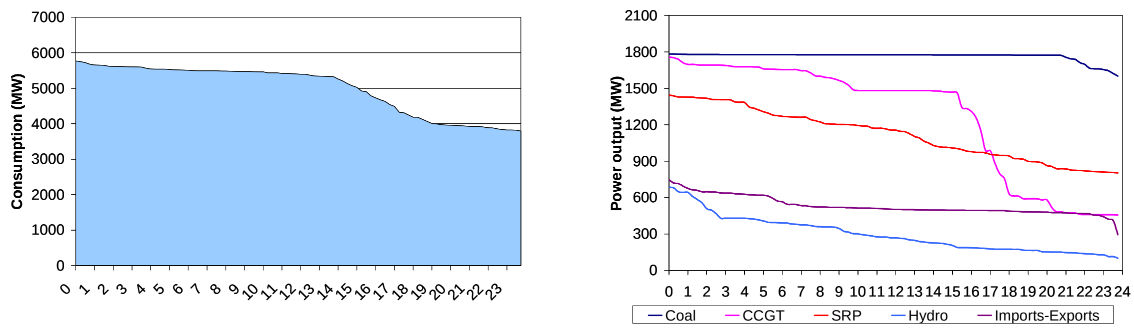


Figure 2.5- LDC for a summer day (17.08.2006). Source: Own elaboration of data collected from REN site in June 2007.

Both Figures present examples of the load duration curve (LDC) for the total demand and for each technology. The LDC shows the number of hours over the course of a day during which the load exceeds a certain value. For example, according to both figures coal power plants operate at full load during most of the day. On the other hand, the SRP, hydro and interconnection balance loads are unstable and the LDCs present a decreasing trend indicating that the maximum output is only achieved for a short period of time.

In coal power plants which are less flexible, the more economic units are loaded first and are operated in a continuous basis. Combined cycle gas turbine (CCGT) units are also operated as baseload units, but with a little more flexibility resulting in a less stable output. More costly units, like fueloil and gasoil plants are loaded last, in order to cover peak electricity demand. Hydro power plants and interconnection trading present a less regular output during the day and may be used to cover peaks or as immediate response to demand or supply changes. SRP (small hydro, other renewable sources and the cogeneration) are not included in the dispatching process of the system manager. These producers have priority access to the grid and thus must be considered to contribute to the base load, although their output is much more unstable than conventional base load thermal power plants.

Based on REN (2005) forecasts, an increase of about 35% of the total installed electricity generation capacity between 2006 and 2011 may be expected, followed by an additional 24% increase in the period 2001-2016. Figure 2.6 shows the distribution of the total installed power in 2006 and the forecasts for the following years. This Figure also presents the total electricity consumption in 2006 and future expected values for 2011 and 2016.

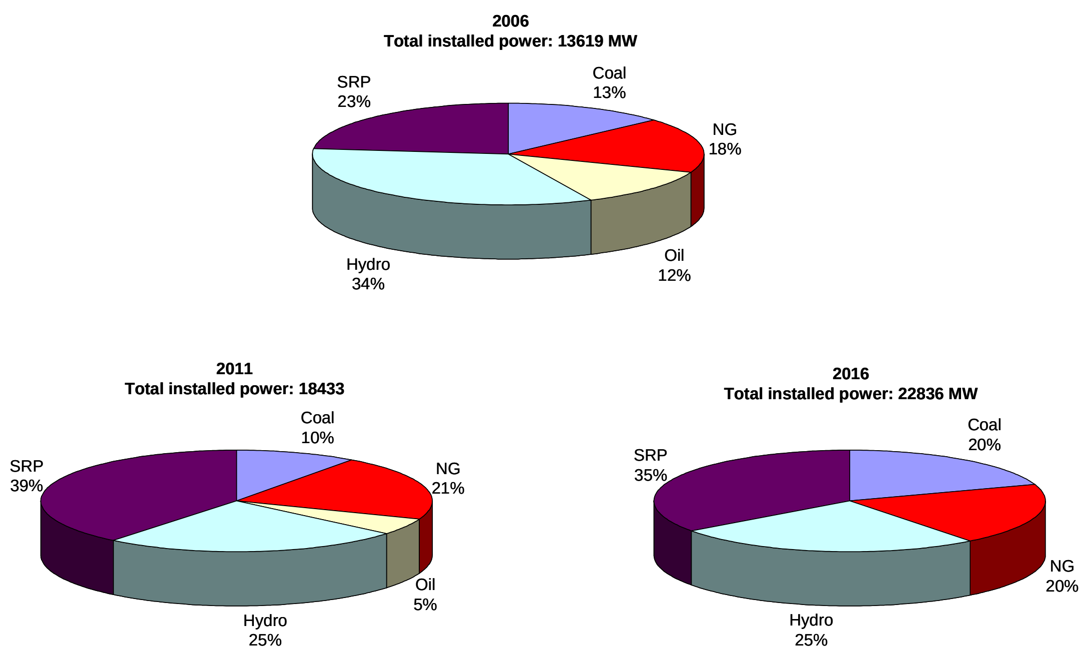


Figure 2.6- Distribution of the total installed power in 2006 and forecasts for 2011 and 2016. Source: Own elaboration of REN (2005a and 2007a) and DGGE (2007).

According to these forecasts there will be a reduction of both thermal and large hydro power quotas and a large increase of the SRP quota, in percent terms. All the energy sources will grow in absolute terms, with the exception of oil power due to the dismantling of the power plants presently consuming it. Thermal power will increase exclusively due to the growth of the natural gas power groups up to 2013. After that, REN (2005) scenarios assume new investments both in coal and natural gas. The growth of the SRP will be mainly driven by the increase of the renewable energy sector, in particular wind. According to these scenarios, the wind sector will achieve about 25% of the total installed power by 2011.

The future of the electricity power systems is strongly constrained by international environmental agreements, namely the Kyoto protocol and RES Directive. The Portuguese strategy for the electricity system, based on RES and natural gas growth, is fundamental to the accomplishment of these goals. The evolution of the hydroelectric sector along with the SRP is part of this strategy for the electricity system, representing a clear effort for the promotion of endogenous resources, reduction of external energy dependency and diversification of supply. The combined growth of natural gas and coal allows for a mixed thermal system and contributes to the reduction of Portugal's strong dependence on oil, although the transportation sector still plays a major role in this matter.

Figure 2.7 presents the evolution of electricity production from RES in Portugal (excluding islands). The picture does not include photovoltaic production due to its low contribution; in 2006 this RES represented less than 0.02% of the total electricity production from RES.

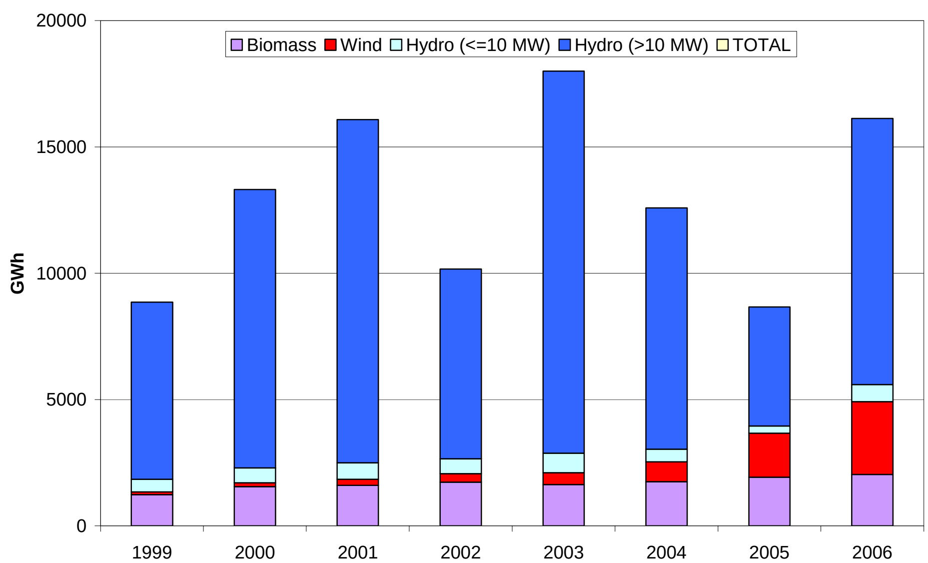
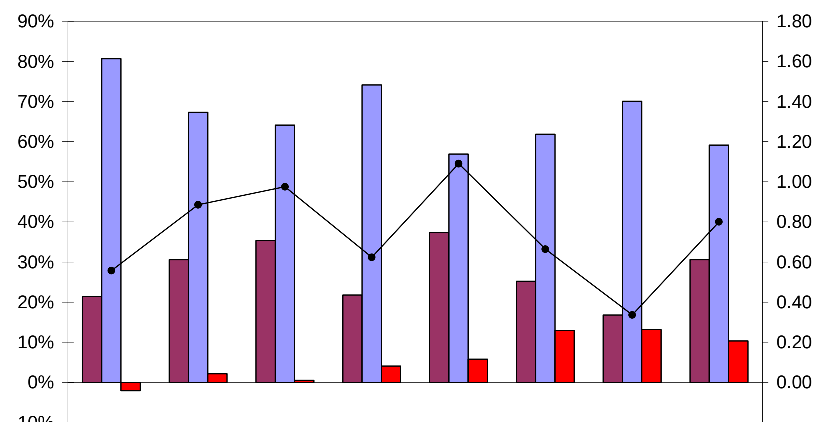


Figure 2.7- Electricity production from RES in Portugal (excluding islands), 1999-2006. Source: Own elaboration of DGGE (2007) data.

It has become apparent that large hydro generated electricity is the most important RES, with a contribution of 65% of the total RES production in 2006. This is followed by wind power production with a 18% share, biomass with 13% and small-scale hydro with 4%. Thus, the total RES production is extremely vulnerable to the rainfall conditions. Between 1999 and 2003, the total large hydropower installed capacity remained unchanged; however its total production suffered strong variations. Dry years like 1999, 2002 and 2005 led to small RES production, whereas wet years like 2003 led to large RES production. Between 2003 and 2005, the installed large hydropower grew more than 10%, however its production in 2005 (an extremely dry year) was reduced by almost 70% in relation to 2003.

The strong role of the hydropower production in Portugal becomes evident when analysing the distribution of the electricity production between hydro, thermal and RES. Figure 2.8 presents this distribution between 1999 and 2006 for mainland Portugal, and indicates the Hydraulic Productivity Index (HPI) for each year. The HPI relates the hydropower production during a time period and the hydropower production that would be obtained under average hydro conditions.



	1999	2000	2001	2002	2003	2004	2005	2006
Renewables	21%	31%	35%	22%	37%	25%	17%	31%
Themal	81%	67%	64%	74%	57%	62%	70%	59%
Imports-Exports	-2%	2%	1%	4%	6%	13%	13%	10%
HPI	0.56	0.89	0.98	0.62	1.09	0.66	0.34	0.80

Figure 2.8- Thermal and hydro electricity production, electricity import balance and HPI in Portugal (excluding islands), 1999-2006. Source: Own elaboration of DGGE (2007) data.

In 1999, the thermal power production represented more than 80% of the total electricity consumption. This was a year with a modest HPI, leading to a reduced share of electricity produced from RES. The same happened in 2002, however the reduced hydro production was compensated not only by the thermal sector but also by the electricity importations.

The driest year included in the analysis was 2005. Hydro power production accounted for less than 10% of the total electricity consumption, but the growth of wind power production partially compensated this loss in renewable energy production and the thermal power share was smaller than in 1999 or 2002. In contrast, in 2003 the thermal power production share was only 57% and the electricity production from RES represented 37%, taking advantage of the wet regime of the year.

In the future, the large hydro sector will maintain a dominant position. However, the wind power sector is expected to increasingly gain in importance. Between 1997 and 2006, the electricity production from wind presented a significant growth, from a 1% share of RES in 1999 to 18% in 2006. In order to accomplish the goals set by Directive 2001/77/EC, national targets were established. Ministerial resolution 63/2003 set the target of reaching 3750 MW of installed wind power in 2010. A further Ministerial resolution, 169/2005, increased the wind power target to 5100 MW between 2012 and 2013. In order to accomplish this, the government launched a tendering procedure for the development of an additional 1500 MW capacity for wind power generators.

II.5 The wind power sector in Portugal

Figure 2.9 presents the evolution of the annual and accumulated installed wind power, in Portugal (excluding islands) between 1999 and March 2007. It also indicates the capacity under construction in March 2007.

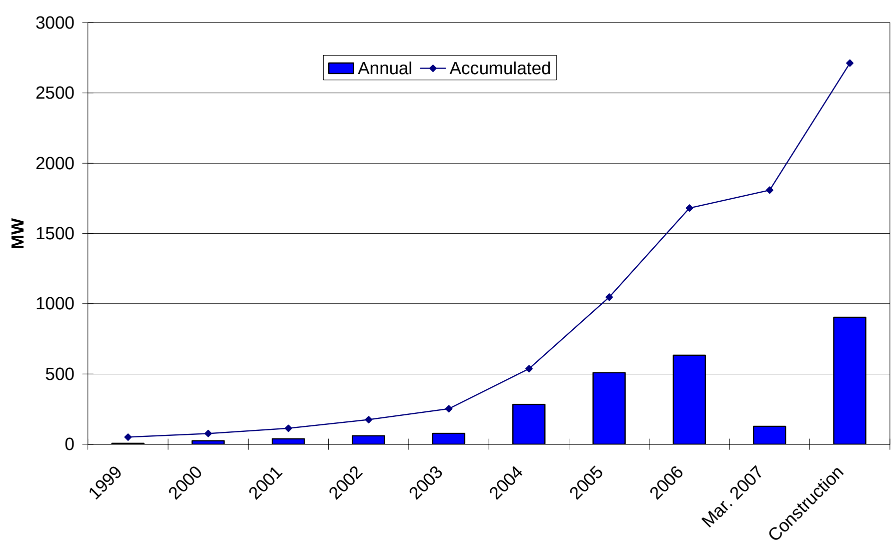


Figure 2.9- Installed wind power in Portugal, 1999-2007. Source: Own elaboration of DGGE (2007) and Rodrigues (2007) data.

During these years, the installed wind power grew at an average annual rate of 57%, equivalent to 204 MW per year. This growth was especially noticeable in the late years, reaching more than 600 MW in 2006. According to DGGE (2007) data, the total installed power was about 1808 MW in March 2007. In the future, this growth trend should continue, due to the remaining capacity already under construction or awarded to the promoters and the additional capacity released by the tendering procedure. The perspectives are that the total installed wind power may reach values close to 5100 MW in the near future, as described in Figure 2.10.

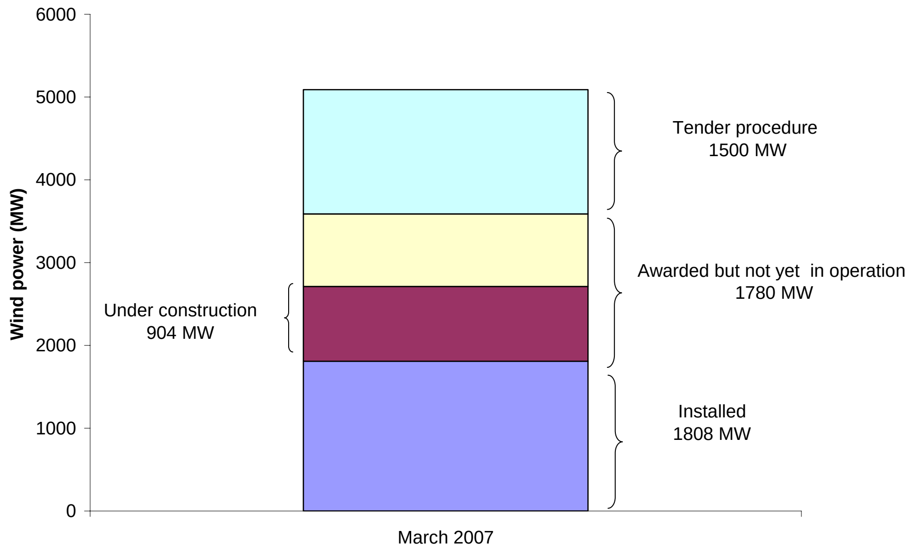


Figure 2.10- Wind power in Portugal: installed and already endorsed to the promoters.
Source: Own elaboration of DGGE (2007), Rodrigues (2007) and REN (2007a) data.

According to REN (2005) forecasts, in 2011, the total installed wind power will represent about 41% of the annual forecasted peak demand and 16% of the gross electricity consumption on Mainland Portugal[17]. When comparing this later value with the three European leading countries in wind power capacity, it is clear that this represents an ambitious goal. In fact, the Danish wind power production represented about 17% of the total electricity consumption in 2006, whereas in the same year this value was 9% for Spain and 5% for Germany[18].

However, these countries possess strong interconnected electricity systems with at least three neighbour countries, which is crucial for security of supply. For example, Denmark

[17] Own calculations based on REN (2005) and assuming an average 26% load factor for wind power plants.
The load factor is a measure of the electricity that a power plant produces during a certain period compare to the maximum possible production level over the same period.
[18] Own calculations based on EuroObserv'ER (2007) and Eurostat (2007).

had an import capacity in the 2006/2007 winter equivalent to about 24% of its total capacity. Portugal is interconnected only with Spain and, in the 2006/2007 winter, its import capacity was equivalent to less than 9% of its total capacity[19]. In addition, Germany and Spain are backed up by strong thermal, nuclear and hydropower systems, resulting in high reserve margins. In 2006, the reserve margin was 81% in German and 95% in Spain[20]. According to REN (2005) forecasts, between 2006 and 2011 the Portuguese peak demand will grow about 27%. For the same period, a 35% increase of the total installed power is predicted, meaning that the reserve margin will grow from the present 70% to 81%. This rise results largely from the need to face increasing demands for electricity but also from the need to deal with the increasing variability of the power output, due to the intensive use of wind energy.

The large penetration of wind power in Germany influences significantly the power balance of the public electricity supply. The Association of German electricity network operators (VDN, 2005) states that the non-usable capacity (capacity which cannot be freely deployed) of the system, "(…) increases distinctly from year to year, mainly due to the fact that a large part of newly constructed wind generating capacity is considered to be not usable as a result of unsteady availability of wind.". Likewise, the ESB National Grid (2004) study for Ireland concludes that the capacity credit for wind power[21] rises more slowly with increasing wind shares. Thus, the amount of conventional plants that may be replaced by wind plants decreases progressively and tends to zero.

The improvement of interconnection capacity is a key requirement for ensuring the security of supply. The geographical location of Portugal (bordering only to Spain and the Atlantic Ocean) implies that the Portuguese system may only be interconnected to the European grid through Spain. The European Commission recognizes the need for the electricity network reinforcement in Portugal-Spain, and this project was included among the nine priority axes of the trans-European electricity network in the EU (European Commission, 2004). In addition, the planning studies of the Portuguese generating system concluded that the use of hydro schemes with reversible capacities is the most appropriate

[19] Own calculations based on Indicative values for Net Transfer Capacities (NTC) published by the European Transmission System Operators (www.etso-net.org) and Danish Energy Authority (2007).

[20] Own calculations based on REE (2006) and VDN (2007).

$$\text{Reserve margin} = \frac{\text{Installed power} + \text{Importation capacity} - \text{Peak demand}}{\text{Peak demand}}.$$

[21] The capacity credit of wind represents the amount of conventional generation that can be displaced by wind generation, without affecting the reliability of the total system.

solution to ensure the adequate levels of security of supply. Therefore, according to Esteves et al. (2003) it is fundamental to proceed with the planned hydro schemes in order to avoid possible situations of operational reserve deficit. At the same time, these hydro schemes represent an important contribution to the accomplishment of the renewable goals established for Portugal.

II.6 Concluding remarks

In this chapter the Portuguese electricity system was characterised and the future prospects were presented, exposing the major weaknesses of the system. The Portuguese electricity sector heavily relies on fossil fuel imports and the main domestic resource for electricity production is hydro power, making the system highly dependent on external energy resources and on rainfall conditions. In addition, the increase of electricity consumption shows a trend much stepper than most of the other EU countries and the electricity intensity of the economy is still rising. Predictions for the next years indicate that the electricity consumption will continue rising, reaching in 2016 a value 55% higher than in 2006.

The need for a cleaner and more efficient electricity system calls for the implementation of energy strategies envisaging the reorganisation of the market, the promotion of energy efficiency and the reduction of fossil fuel dependency. The combination of better efficiency both at energy system transformations and among the final consumers, with strong investments on RES technologies is fundamental for managing external dependency of the country and for boosting the environmental performance of the energy sector.

The move towards renewable energy technologies is strongly stressed in the government policy for the sector and the response of the industry has been positive, in particular in regard to wind power. During the next decade, the structure of power generation is expected to change significantly in favour of renewables. Large hydro is still the dominant renewable energy resource in Portugal but wind power is closely following it and the RES development is mainly driven by the high growth rates of wind energy. At the end of 2006, the total wind power capacity reached a value close to 1700 MW, putting Portugal amongst the top European wind power producers. Forecasts for the sector clearly indicate that this trend will continue, with the installed power in Portugal expected to overcome the current

Danish values within a decade.

The increasing demands of electricity and to some extent the higher penetration of technologies of variable output require higher generation capacity in Portugal, based not only on investments in renewable energy technologies but also on new coal and natural gas power plants. The increase of both the power reserve and of the interconnection capacity, seem to be fundamental means to preserve the security of supply. The specific characteristics of the Portuguese electricity system give rise to considerable challenges to the planner. Aspects such as a high dependency of the system on rainfall, the management of a diversified mix of technologies presently operating in the system, the expected impacts of the RES development, the increase in energy demand, and the regulatory environmental policies must be taken into consideration.

CHAPTER III

SUSTAINABLE ENERGY PLANNING: AN OVERVIEW OF THE LITERATURE

This chapter presents a review of the literature establishing the link between sustainable development and energy and in particular with renewable energy sources (RES). Different energy planning models are described, giving special attention to models addressing the impact of RES and resorting to participation techniques to formulate and implement energy plans.

III.1 Introduction

Energy use and availability are central issues in sustainable development. Energy is essential for economic development and for improving society's living standards. However, political decisions regarding the use of sustainable energy must take into account social and environmental concerns.

The most common definition of sustainable development is the one provided by the the Brundtland Report "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (World Commission on Environment and Development, 1987). In general, definitions of sustainable development focus on three main aspects: economic, environmental and social. As the World Bank (2003) report states "Improving human well-being over time is a broader goal than increasing economic growth (..) social and environmental assets also affect human well-being directly". Also Hopwood et al. (2005) defines the concept of sustainable development as an attempt to combine concerns about environmental issues with socio-economic issues. Langer and Schön (2002), highlight the role of proper evaluation for sustainable development as an instrument to ensure and verify the integration of social, economic and environmental policies. This quest for integration makes the policymaking processes more complex and creates additional problems with the weighting of the different dimensions of sustainable development (Martinuzzi, 2004).

The thinking about social sustainability is not yet as advanced as for the other two pillars (World Bank, 2003). Until recently, sustainable development was perceived as an essentially environmental issue, concerning the integration of environmental concerns into economic decision-making (Lehtonen, 2004). For example, for the particular case of the role of renewable energy sources (RES) to sustainable development, Del Río and Burguillo (2007) support the view that much emphasis is being put on the environmental benefits while socioeconomic impacts have not received a comparable attention.

The three dimensions of sustainable development are intrinsically linked. As the G8 Renewable Energy Task Force (2001) recognises "Economies can only grow if they are not threatened by environmental catastrophe or social unrest. Environmental quality can only be protected if basic economic needs are fulfilled and individuals take responsibility for public goods. Finally, social development rests on economic growth as well as a healthy environment.”

The economic, social and environmental perspectives are all included in the key elements of a sustainable energy system listed by Jefferson (2006): sufficient growth of energy supplies to meet human needs, energy efficiency and conservation measures, addressing public health and safety issues and protection of the biosphere. Thus, the sustainable development and sustainable energy planning are based on the same three dimensions, viz., economic, environmental and social.

In the following Section (III.2) of this Chapter a review of the literature is presented establishing the link between sustainable development and energy and in particular with RES. Section III.3 looks at the energy planning process. It begins with a preliminary discussion of the electricity planning process and discusses the different planning horizons: long term, mid term and short term. Section III.4 presents a description of the existing energy planning models addressing the question of criteria valuation and public involvement in the energy decisions. The electricity planning with RES is treated in Section III.5. The last Section presents the concluding remarks.

III.2 Energy and sustainable development

The increasing acceptance of the principle of sustainable development has been a major driving force towards new approaches to energy planning. Achieving the goal of sustainable development implies recognising and including the social and environmental impacts of the energy sector in the decision making process. These impacts are frequently described as external costs or externalities of the activity.

Externalities may be defined as the unpriced costs and benefits which arise when the social or economic activities of one group (agent) of people have an impact on another. As an example, electricity production activities cause environmental damages which associated costs are not borne by the producers or consumers of that electricity. The externalities reflect the damages to the human health and the environment. There are several ways of taking account of the cost to the environment and health, i.e. for 'internalising' external costs: via eco-taxes, subsidising cleaner technologies thus avoiding socio-environmental costs or using evaluation methods such as cost benefit analysis or life-cycle analysis (European Commission, 1995a and ExternE site[22]). These mechanisms intend to contribute to the convergence of private and social costs, also creating incentives for profit maximising firms to select projects that simultaneous satisfy environmental and economic goals.

Similarly, the Energy Information Administration (1995) defines externality as "benefits or costs resulting as an unintended byproduct of an economic activity that accrue to someone other than the parties involved in the activity". In line with this definition, the Asia Pacific Energy Research Centre (APERC, 2005) classifies externalities as any economic activity that results in a liability (or benefit) to a third party, but is not reflected in its price. Examples for the power generation sector include environmental degradation, impact on public health, water and land pollution, in addition to the concerns surrounding global warming from fossil-fuel combustion.

According to the International Institute for Sustainable Development (Venema and Barg, 2003) externalities constitute a loss of social welfare due to their negative human health and ecological impacts and they are considered external to the market price for a product. Although frequently reports on externalities focus on the external environmental costs of the activities, the Nuclear Energy Agency (2003) recalls that externalities of energy are not limited to environmental and health related impacts, but may result also from macro-economic, policy or strategic factors not reflected in market prices, such as security of supply, cost stability and broad economic impacts on employment and balance of trade.

The socio-environmental issues associated with energy systems from primary extraction to the processing of fuels, and from energy conversion to electricity distribution and use are extremely complex (Bardouille, 1999). From the business perspective, traditionally the decision investment process has been based on the analysis of the financial viability of the project and the non financial dimensions were treated as externalities. However energy sustainability principles imply all three dimensions should be taken into consideration also at business level.

[22] http://www.externe.info/

Changes in energy use from fossil fuel to renewable sources will offer market opportunities for businesses generating economic and social benefits as well as protecting the environment. However, the market may need modification to redress market failure and regulation to achieve ecological sustainability. According to Streimikiene et al. (2007), in the particular case of energy, sustainable growth can only be achieved through a regulatory framework, which complies with the rules of a competitive market. The authors point to three market failures which hamper sustainable energy development:

- negative externalities caused by pollution or external costs. A firm investing in or implementing new clean technologies typically generates benefits for others and incurs all the costs, while the polluter gets the benefits derived from polluting and imposes the pollution costs on others;

- positive externalities associated with innovations and diffusion of new environmentally friendly technologies. An investing firm cannot keep other firms from also benefiting from their new knowledge and therefore cannot capture for itself all the benefits of the innovation;

- and the problem of incomplete information or asymmetry of information. The information about the prospects for success of a given new technology is asymmetric and it is a risky investment. Frequently, capital for funding of new technology development and diffusion requires state interventions in promotion of new environmentally friendly, energy efficient technologies.

The need to incorporate the environmental aspects in energy decisions may come from the increased environmental awareness amongst consumers and the consequent financial losses for companies with poor environmental performances. This is then associated with the strategic dimension of the project. The creation of environmental taxes directly related to the emissions represents a clear way to incorporate the environmental costs in the project costs, penalising the more polluting ones. An example is the UK Climate Change Levy, an energy tax introduced in April 2001 as part of the strategy to promote energy efficiency and reduce greenhouse gas emissions.

The Kyoto protocol opened the way to the CO_2 (Carbon Dioxide) market and to the assignment of a value to these emissions, representing a new operational cost for projects releasing CO_2 to the atmosphere. The importance of this new cost on the investment decision may be seen in articles like Saleiro et al. (2007), comparing the investment on a new Combined Cycle Gas Turbine (CCGT) with an investment in a new wind farm in Portugal. The authors concluded that the assignment of a financial cost to some of what were previously considered to be externalities of the projects could easily change the total cost relationship between the two technologies.

Under conditions of sustainable energy planning, the profitability of energy companies and the financial viability of energy projects become highly dependent on non financial factors. The simultaneous assessment of economic, strategic, social, environmental and technical aspects is fundamental for making professionally correct investment decisions in any sector[23]. However, it is particularly important for the energy sector, traditionally associated with large scale projects with strong and conflicting social impacts: on one hand these projects are absolutely indispensable for the social welfare of the population but on the other hand they are frequently associated with environmental problems and have to deal with social opposition.

National or regional resource planning has expanded beyond financial cost alone and energy planning and strategies must be based on full social cost. The focus of energy planning is now on the prospective evaluation of energy projects integrated in a whole energy system rather than independent projects. Such planning serves as an instrument to ensure and verify the integration of social, economic and environmental policies. This quest for integration of these three dimensions, demonstrates the close relationship between long range energy planning and sustainable development principles. Changing course towards sustainability will often require altering the pattern of preferences, the resource intensity of technologies, or the relevant time horizon for different decisions (World Bank, 2003).

Proper selection of energy technologies for the future represents a valuable contribution to meeting sustainable energy development targets. Hepbasli (2007) states that energy resources and their utilisation is intimately related to sustainable development and a

[23] The inclusion of non-financial aspects in project evaluation is debated at some length in a previous work from the authors (Ferreira et al., 2004).

sustainable energy system must fulfil the requirements of being cost-efficient, reliable, and environmentally friendly. Also Dincer and Rosen (2005) state that, sustainable development requires a sustainable supply of clean and affordable energy resources that do not cause negative societal impacts. Similarly, Lund (2007) supports the view that sustainable development involves energy savings on the demand side, efficiency improvements in the energy production, and replacement of fossil fuels by various sources of renewable energy.

The rapid depletion of energy resources and the new mechanisms for assigning significant costs to more polluting projects, converges to an understanding that the long term economic gains and environmental protection rather than being conflicting objectives are indeed complementary. As an example, the increasing natural gas prices and CO_2 allowances market, represent new competitive advantages for electricity production projects based on RES, reducing the gap between production costs of CCGT and wind power plants in particular. Taking a long term view, large renewable investments can make an effective contribution to the minimisation of the electricity production costs from the financial, environmental and social points of view.

III.2.1 RES for sustainable development

The importance of renewable energy for sustainable development is recognized and well documented in declarations from several organisations and institutions. Figure 3.1, presents some of the many statements that clearly establish a link between sustainable development and the utilization and dissemination of renewable energy technologies.

Renewable energies have a fundamental role in providing energy at an acceptable cost avoiding negative impacts on economic growth and, at the same time contributing to a reduction of the greenhouse gas emissions. Technical problems exist but, according to Omer (2007), the biggest problems are more to do with politics and policy issues. Del Río and Burguillo (2007) present an extensive and recent review of the literature on the contribution of renewable energy deployment to sustainable development, and argue that the deployment of renewable energy projects may contribute to the three dimensions of sustainability at local and regional level.

Kyoto protocol Article 2:

"Each Party included in Annex I, (…) in order to promote ***sustainable development****, shall:*

a) Implement and/or further elaborate policies and measures in accordance with its national circumstances, such as:
(…)
(iv) Research on, and promotion, development and increased use of, new and ***renewable forms of energy***"

Commission of the European Communities (2007b):

"The EU has compelling reasons for setting up an enabling framework to promote renewables. They are largely indigenous, they do not rely on uncertain projections on the future availability of fuels, and their predominantly decentralised nature makes our societies less vulnerable. It is thus undisputed that ***renewable energies*** *constitute a key element of a* ***sustainable future****."*

Communiqué G8 Genova summit, 22 July 2001 (G8, 2001):

"We recognise the importance of ***renewable energy*** *for* ***sustainable development****, diversification of energy supply, and preservation of the environment. We will ensure that renewable energy sources are adequately considered in our national plans and encourage others to do so as well. We encourage continuing research and investment in renewable energy technology, throughout the world. Renewable energy can contribute to poverty reduction."*

Report on the fifteenth session of the United Nations Commission on Sustainable Development 30 April-11 May 2007 (UNCSD, 2007):

"The policy options and possible actions that can be considered at the international level to support implementation efforts for energy for ***sustainable development*** *include:*
(…)
(n) Increasing technology cooperation programmes, with international support, to accelerate the diffusion of ***renewable energy technologies****, such as in the areas of solar photovoltaic and thermal energy, wind power, small-scale hydropower, geothermal energy, mini-hydropower and biogas, (…)";*

Figure 3.1- Importance of renewable energy for sustainable development.

Renewable energies present important characteristics that make them particularly interesting for realising sustainable development goals, helping to balance economic, environmental and social dimensions:

- They help to reduce environmental problems.

    - Normally their environmental impact is low. Almost none of them release pollutants during operation (Hepbasli, 2007) and they help to reduce CO_2 (Bilen et al., 2007). Works like Dincer and Rosen (2005) and Commission of the European Communities (2007a) support the view that widespread use of renewable energy systems would certainly reduce pollution levels.

- They contribute to a reduction of the external dependency of the countries, usually highly dependent on the importation of fossil fuels.

    - RES contribute to security of supply by increasing the share of domestically produced energy, diversifying the fuel mix, diversifying the sources of energy imports and increasing the proportion of energy obtained from politically stable regions (Commission of the European Communities, 2007a).

- They can not be depleted, in comparison to fossil fuel and uranium resources that are diminished by consumption.

- Electricity generated by RES may be fed into large grids, but also have a fundamental role on the decentralised energy production and supply.

    - It allows supplying remote areas using endogenous resources removing important obstacles to local development (Bilen et al., 2007). System decentralisation and local solutions that are somewhat independent of the national network enhance the flexibility of the system and provide economic benefits to small isolated populations (Dincer and Rosen, 2005).

    - This decentralisation characteristic promotes local development and creates new employment opportunities in poor, isolated regions. Electricity generated by RES provides important social and economic benefits in rural areas.

    - There are positive income generation effects for the local community. The most relevant are payments to local farmers for hiring their land and ‘‘compensations’’ to the local community made by the owner of the renewable energy plant (Del Río and Burguillo, 2007).

- RES are relatively independent of the cost of oil and other fossil fuels.

- The cost of renewable energy is largely a function of initial investment costs. Estimates can be made reliably for these and future costs present low uncertainty (Dincer and Rosen, 2005, Bilen et al., 2007).

- Renewable energies do not rely on uncertain projections on the future availability of fuels, reducing also the exposure to fossil fuel price volatility (Commission of the European Communities, 2007b).

➢ In contrast to conventional energy sources, there has been a continued and significant reduction in the cost for renewables over the last 20 years (Commission of the European Communities, 2007b).

  - If external prices are reflected in energy costs RES can compete with conventional fuels (Commission of the European Communities, 2007b and G8 Renewable Energy Task Force, 2001).

  - The high initial investment of renewable energy plants often constitutes a major barrier to their wide spread use (Abulfotuh, 2007), but some RES technologies are maturing rapidly and are increasingly cost competitive (G8 Renewable Energy Task Force, 2001).

➢ RES have a strategic value for countries and contribute to increase competitiveness creating also new business opportunities.

  - At the EU level, it is expected that further business opportunities will arise from the export of renewable energy technology (Commission of the European Communities, 2007b).

  - They also have a strategic value due to their low operating costs, modularity and very short construction times, which confer greater flexibility to energy planning and investment (G8 Renewable Energy Task Force, 2001).

Figure 3.2 summarises the contribution of renewable energy sources to the three dimensions of sustainable development.

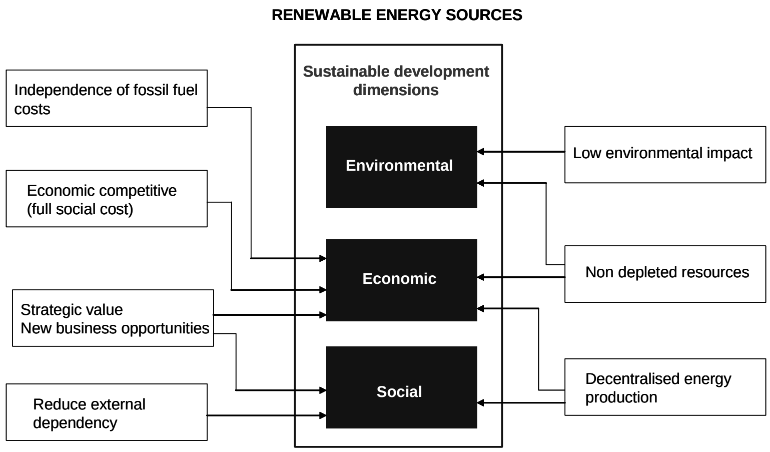


Figure 3.2- Renewable energy link to the three dimensions of sustainable development.

Decision support frameworks in the energy sector and in particular in energy planning with RES included, must be able to accommodate complex economic, environmental and social interactions. All the relevant attributes of the energy alternatives must be balanced and interwoven, allowing for a comprehensive analysis recognising the full impacts of RES in promoting sustainable energy development.

III.3 Energy planning

Energy planning is a complex process involving multiple and conflicting objectives with many agents able to influence decisions. The integration of environmental, social and economic issues in decision making although fundamental is not an easy task and tradeoffs must be made. As Bruckner et al. (2005) note this is an ever changing field, depending on aspects like policy issues, advances in computer sciences and developments in economics, engineering and sociology.

Hobbs (1995) classified energy planning according to the time length and objectives, including for example resource planning, long range fuel planning, maintenance, unit commitment and dispatching. Considering the particular case of the electricity system, three main types of planning could be described, with differences deriving mainly from the time horizon considered in the planning process:

- **Long-range resource planning.**

  - The time horizon ranges from 10 to 40 years. This planning is largely associated with strategic decision making. The aim is to find the least cost mix of generator additions and retirements considering long range forecasts of demand, fuel prices and regulations (Hobbs, 1995). The process frequently involves multiple objectives, like cost, emissions and social criteria.

- In a deregulated market and from the planning perspective within the organisation point of view, Dyner and Larsen (2001) call this process the strategic planning of the companies. It includes making decisions on matters such as alliances, long-term contracts and capacity investment. The decision to construct a new plant is based on economic analysis and on the ability to obtain financing for the project (Mazer, 2007).

➢ **Mid term planning.**

- It is associated with operational planning or programming of an electricity system given the available equipment. For example, the yearly planning establishes the optimal operation of the system for the next year taking into consideration the expected demand, trading across interconnectors with other systems, water inflow, planned maintenance of the plants and legal requirements. Shorter term exploration planning (monthly for example) will make the necessary corrections to the yearly planning using more accurate forecasts and additional information obtained in the meanwhile.

- In a deregulated market the medium-term decisions within the electricity generation organisation may be called tactical (Dyner and Larsen, 2001). The operational issues include the maintenance scheduling and planning the use of limited energy resources. The process involves risk management activities and the producers and retailers frequently resort to wholesale selling financial products to manage the financial risk (Mazer, 2007).

- **Short term planning.**

  - The unit commitment is part of the process, with time horizon ranging from one week to 8 hours (Hobb, 1995). The aim is to define a programme of operations that minimises operational costs, given the load, the characteristics of the available generators and legal requirements in respect to operators. In this time frame, decisions must be made on which generating units to start, so that they are available when needed. The unit-commitment decision must be made well in advance because of the relatively long time required to start and stop some types of generators. Once units have been committed, they can be used to provide capacity and energy to the grid. Loads will vary during the day, so some of the units that are online will ramp up or down to match the load (Dragoon and Milligan, 2003).

  - The dispatching process, with time horizon of a few minutes, is frequently based on the day ahead scheduling against the forecasted load and on a merit order that will allow calling generators to the system in real time in order to maintain voltages and frequencies. The merit order represents an ordered list of generators established according to their prices or variable costs for electricity production (REN, 2002a).

  - In a deregulated market the short-term decisions within the electricity generation organisation may be called operational (Dyner and Larsen, 2001). The planning is based on asset management and includes making decision on bidding price, strategy and availability (Dyner and Larsen, 2001 and Mazer, 2007).

The centralised long range resource planning is mainly concerned with socio-economic policy making. It is dedicated to decision-making on the choice of technologies, given objective functions and some constraints. The decision model used identifies which technologies should be chosen to get as close as possible to the objective (Boulangera and Bréchet, 2005). Frequently there is more than one objective to consider and there is a plurality of decision-makers with different preferences and expectations.

On the other hand, the mid and short term planning mainly consist of making production decisions aimed at meeting demand with an adequate security level and taking into consideration cost and emissions objectives. As the time horizon gets lower, the accuracy of the forecasts available to the planners gets better and new decisions must be made in order to accommodate possible changes and even regulate production in real time. This type of planning assumes as a given input the technologies available in each period and is based on the specific characteristics of the generators in the system.

The energy planning process also includes other aspects beyond capacity expansion or the generation scheduling and commitment, namely the transmission and distribution network planning and the reactive power compensation planning as described in detail by Diakoulaki et al. (2005). However, the focus of the present work is on the particular aspect of capacity expansion planning and whenever the expressions "energy planning" or "electricity planning" are used from here onwards, the author is referring to this long range problem.

The question of electricity planning in deregulated markets is discussed by several authors, with particular emphasis on the question of uncertainty in these markets. Dyner and Larsen (2001) detail this issue and present an analysis on how the planning methods used under monopoly have to change to take the new deregulated environment into account. During the monopolistic age, electricity prices were often stable, full information was available resulting in low uncertainty, forecasts of the aggregated demand were also available and were appropriate for the planning process and finally a cooperative working environment existed between the regulator and the monopolistic company. On the other hand, in a deregulated market the uncertainty is high: prices fluctuate, information is limited, companies must focus on changes that might occur to their market share. This market share, depends on the company's own as well as its competitors' actions and it is much more difficult to predict than the aggregated demand.

According to Dyner and Larsen (2001), the centralised long range planning models are used more as a way of creating a benchmark for the companies' planning process. The uncertainty is high and companies' long range planning must include tools based on traditional strategic management frameworks, behavioural simulation, financial analysis and scenarios. The authors review some of the tools that companies may consider using when they formulate strategies in deregulated markets.

Also Diakoulaki et al. (2005) recall that most of the developed models for long range planning require generation capacity expansion to be mainly centrally planned. But, as the authors pointed out, this situation corresponds to a large number of cases, either because electricity markets were not liberalised or, even after liberalisation, they kept some fundamental characteristics of the traditional organisation. Although under restructuring States will no longer oversee the entire process of development and investment in new generating capacity, State entities still wield significant power to influence investments through licensing and permitting processes, through the terms of interconnection agreements, and more generally, through State decisions regarding whether and how far to pursue restructuring of their retail market (Walls et al., 2007).

Hobbs (1995) presents three reasons for the increased complexity of the energy planning process: the increasing number of options, the great uncertainty in load growth, fuel markets, technological development and government regulation and finally the inclusion of new objectives other than cost. Different authors and studies use different approaches for solving these complex energy planning problems. These approaches include for example several multicriteria tools, the monetisation (evaluation in monetary terms) of all the criteria, the use of a framework for systematic collection and analysis of information, the use of strategic planning tools or a combination of two or more of these methods. The next section will present some recent examples of works published on energy planning which illustrate the diversity of methods used and applications of these approaches. Special attention is given to methodologies followed by different authors for the integration of RES in their models of electricity generation.

III.4 Energy planning models

In this section an overview of recent papers proposing different approaches to energy planning is presented, with predominant emphasis on the particular sector of electricity. The aim is not to make an exhaustive review of all the methods and models, but rather present some recent examples that will give a broad overview of the planning tools most frequently used, their advantages and drawbacks and fields of application. Diakoulaki et al. (2005) distinguished two broad multicriteria methodologies for dealing with energy planning: multiobjective programming models and the models dealing with discrete alternative options. Also in the study the planning models were classified as single or multiobjective programming models, when involving single or multiobjective optimisation procedures and as discrete models, when involving comparison of scenarios, technologies or projects.

III.4.1 Single or multiobjective programming models

When addressing the energy planning process as a single or multiobjective programming problem, no initial description of the possible discrete solutions or plans is presented. Alternatives are implicitly defined by a set of constraints (Diakoulaki et la., 2005). The energy system is described by mathematical functions and the aim is to find the best solutions according to the objective functions and constraints, relying on single or multiple objective optimisation procedures.

The objective functions generally considered may include the minimisation of the total expansion cost in the planning horizon, the minimisation of environmental damages, the maximisation of the reliability of the supply system, the minimisation of the external dependency of the country and/or the minimisation of a risk potential indicator. The constraints generally refer to aspects like capacity limitations, minimum load requirements, demand satisfaction, resource and operational availability, technology restrictions, domestic fuel quotas, security of the system, budgetary limitations, operational availability of generating units and rate of growth of the addition of new capacity (Diakoulaki et la., 2005).

Two examples of these kind of models for long range electricity power planning applied to real cases in Europe are Cormio et al. (2003) and Linares and Romero (2000).

Cormio et al. (2003) proposed and analysed an energy system using a linear optimisation model, taking into account RES and cogeneration. A single objective function consisted in the total cost, including the fixed and variable costs and the economic estimation of burdens occurred to people and environment. The aim was to determine the optimal mix of technologies for the energy system, subject to several constraints describing the system under consideration. The authors applied the model to an Italian region considering different scenarios according to the different regional economic and environmental policies. The energy system available at the time was assumed as the starting point of the planning horizon.

Linares and Romero (2000), used a different approach to deal with externalities. The work aimed to present a model for electricity planning in Spain based on a multiple objective methodology to combine economic and environmental criteria. The authors formulated a linear compromise programming model and the preferential weights assigned to each objective were derived using an AHP approach. The aim was to establish efficient energy plans for year 2030 and several thermal and renewable technologies were included in the analysis.

Both Cormio et al. (2003) and Linares and Romero (2000) used optimisation procedures to formulate optimal plans. Both studies addressed the environmental impact of the electricity generation technologies and integrated them into the analysis along with traditional cost functions. However social impacts were not detailed and integrated into the models. Although Linares and Romero (2000) used a participatory approach, the authors focused only on comparisons of the quantifiable cost and emissions objectives. In addition, no market constraints were included and no integer variables were added to the models. Thus, the models assume that all considered technologies are available on a continuum and no discrete capacity sizes are assigned to each represented technology.

The need to address power generation expansion problems as discrete phenomena was previously highlighted by Mavrotas et al. (1999). The authors presented a model developed for planning the expansion of the Greek power generation system, with two objective functions (economic and environmental emissions) and several operational constraints. The model included integer variables, denoting the number of each type of power units considered for eventual addition to the electricity generation system and continuous variables representing the production output from each power plant and relied on a branch and bound algorithm to solve the problem. The authors included only thermal power plants in the analysis and the social impact of the decisions was not acknowledged.

Sirikum and Techanitisawad (2006), presented an application of genetic algorithms to solve a long-term power generation expansion planning problem described by a non linear mixed integer optimisation problem. The authors used a scaled down version of the Thailand electricity generation system and included only thermal power plants into the analysis. The objective function was the minimisation of the total cost of the power expansion plan. The time horizon ranged from 5 to 30 years divided in 3 time blocks of duration, and it clearly demonstrated the increasing complexity of the model for long term planning due to the rising number of variables. Social impact was not addressed and the environmental dimension was restricted to a set of constraints imposing limits to air pollution.

Antunes et al. (2004) recognised the need to include objectives other than economic in the power generation expansion planning problem. The proposed model considered three objective functions, which quantified the total expansion cost, a measure of the environmental impact and the monetised environmental cost. Thermal power generation units along with Demand Side Management (DSM) options were considered for addition. The authors developed an iterative approach, where the decision makers were required to participate in the process not by assigning weights to the objectives but, by defining their goals at each iteration until the identification of a solution as a satisfactory compromise plan. Previous studies like Martins et al. (1996) had already used similar examples of multiple objective linear programming for power generation planning, to illustrate the application of the TRIMAP method, but included only continuous variables. Another example where TRIMAP was applied is the study by Clímaco et al. (2003) where this and other iterative methods were used to solve a problem of electricity generation expansion planning.

Soloveitchik et al. (2002) analysed multiple objective optimisation models to solve the capacity expansion problem of a power generation system for Israel. The objective function was the minimisation of the total costs values corresponding to the weighted sum of several objective functions, including financial cost and monetary values for pollutants emissions. The computer package CAPEX (developed for the Israeli Ministry of National Infrastructures) was used for optimisation and several penalty coefficients were considered, corresponding to different weights assigned to each objective. As in Antunes et al. (2004), this work also highlights the role of the decision maker in the process: the decision maker has to identify goals that represent his/her aspiration levels for the model to compute the closest alternative to the goal. Once more economic and environmental preferences are dealt with, but the social dimension of the problem is not considered.

Studies like Cormio et al. (2003) and Bardouille and Koubsky (2000) introduced some widelly recognised models/tools based on optimisation procedures and focused on formulating the energy system planning task. An overall description of some of these models and their coverage has also been presented by institutions or organisations like the World Bank[24] or the Community for Energy, Environment and Development (COMMEND)[25].

The EFOM model (Energy Flow Optimisation Model) was developed for the Commission of the European Communities. Lehtila and Pirila (1996) used the extended version EFOM-ENV (Energy Flow Optimisation Model-Environment) to support energy planning in Finland. This is a bottom-up multi period optimisation model subject to a number of conditions and aimed at determining the optimal mix of technologies for the energy system. The system is optimized by linear programming using the total present value costs of the entire energy system over the whole study period as the objective function which is to be minimised. More recently, Holttinen and Tuhkanen (2004) run EFOM for the Finnish energy system to assess the effects of wind power, taking into account capacity expansion during a long time period.

MARKAL (MARKet ALlocation) is another widely used linear model developed by the Energy Technology Systems Analysis Programme (ETSAP)[26] of the International Energy Agency (IEA). Some recent applications of this model include the determination of the wind power generation impact on the future generation mix of the Vietnamese power sector (Nguyen, 2007) or the application of the model to the Japanese energy system, to analyse the potential, based on cost-competitiveness, of photovoltaics generation dissemination (Endo and Ichinohe, 2006). In another study, Unger and Ahlgren (2004) used MARKAL to model the electricity and district-heating supply systems in Sweden, Norway, Finland and Denmark.

MESSAGE (Model of Energy Supply Systems and their General Environmental Impacts)

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[24] http://www.worldbank.org/html/fpd/em/power/EA/methods/tools.stm
[25] http://www.energycommunity.org/default.asp?action=71#times
[26] http://www.etsap.org/Tools/MARKAL.htm

was developed by the International Atomic Energy Agency (IAEA) and it is another linear optimisation model used in medium to long-term energy system planning, energy policy analysis, and scenario development. This model combined with the MACRO model (a macro-economic tool that helps analyse the feedbacks between the energy sector and the economy as a whole), resulted in the MESSAGE-MACRO model described in detail by Messner and Schrattenholzer (2000). Klaassen and Riahi (2007) present a recent example where a MESSAGE-MACRO framework is used to analyse the global results of a policy that internalises the external effects (environmental damage costs) of electricity generation. The combination of MACRO with MARKAL is also reported in studies such as Chen et al. (2007) or Contaldi et al. (2007).

Figure 3.3 summarises the different approaches used in the examples presented above for the energy planning with single and multiobjective programming models.

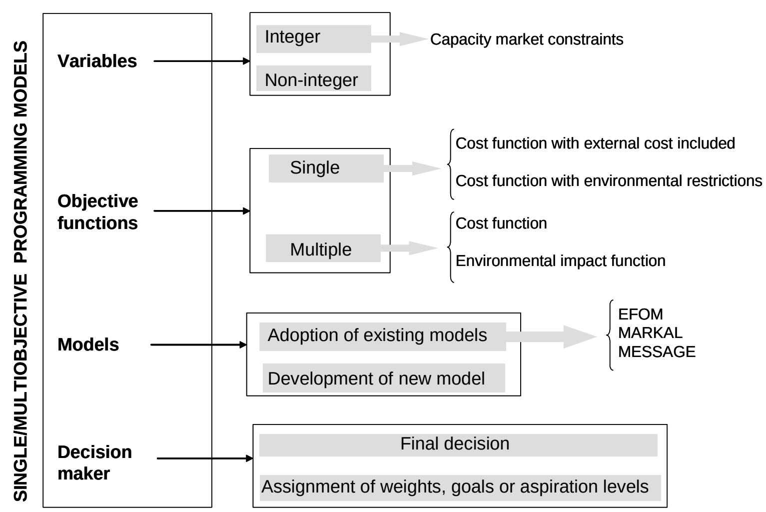

Figure 3.3- Energy planning with single and multiobjective programming models.

Most of these studies are based on complex mathematical models backed up by powerful software systems. They have the advantage of combining a large number of constraints and variables described by mathematical functions. This means that no initial description of the possible scenarios or plans is needed to be presented to decision maker. The outputs of the model are already optimal plans in regard to the objectives considered, obtained from optimisation procedures based on the supplied data and on the functions described.

Optimisation models may involve real and integer variables and include one or more objective functions. The use of integer variables takes into account the discrete nature of the capacity of new plants available in the market. When a single objective cost function is considered in the model, the environmental impacts are usually included in the function as external costs or are included in the model as constraints. The models used may adopt an existing model such as MARKAL, MESSAGE or EFOM-ENV adapting it to each particular case, or may rely on the development of individual models for a region or for a segment of the energy sector like electricity power planning. The obtained plans, representing different tradeoffs among the distinct objectives are then presented to the decision makers for the selection of the final solution. Nevertheless, some models already employ a participative approach, including the decision maker on the assignment of weights or aspiration goals to the considered objectives. However, the more subjective impacts frequently associated with the social dimension of the energy planning problem are not treated explicitly. The social impacts are assumed to be included in the monetary values assigned to the externalities or are not brought into the analysis at all.

According to Lϕken (2007) the main advantages of the single or multiobjective programming methods include their low subjectivity, the straightforward procedure well understood by decision makers and the possibility of using linear programming solvers. However, the complexity of the models is a considerable drawback, along with the need to assign weights to different objectives and the difficulty of integrating non quantitative criteria. Lehtila and Pirila (1996) call attention to major problems of the optimisation models, including the need to keep the model size manageable, the fact that small variations in input parameters can sometimes lead to large variations in the solution and that the most attractive alternatives tend to dominate the solutions, even if the cost differences are low. Also, Jaccard et al. (2003) report that an optimisation model calculates technology shares on the basis of winner-take-all and that small change in costs can lead to dramatic changes in outcomes. The solution found is optimal from the point of view of all information available to the model, disregarding non quantitative aspects which may be difficult to include in the model as constraints.

III.4.2 Discrete models

Discrete models do not involve a description of the objectives or constraints in mathematical functions, but rather a characterisation of a finite set of alternatives aimed to be compared and evaluated. According to Diakoulaki et al. (2005) the main strength of these models is their ability to structure problems that are vaguely defined by providing a deep insight to their components. Energy planning based on discrete models relies on the comparative assessment of alternative scenarios explicitly known a-priori. Each scenario describes a possible expansion plan and gives information about their technical, economic, environmental and social characteristics. A large number of these studies perform comparisons between different electricity power production options, technologies or projects. Following Lϕken's classification (2007), the discrete models may be divided in value measurement models, where a numerical score is assigned to each alternative and outranking models, where the alternatives are compared to choose the preferred one. A few examples of application of these models are presented below.

- **Value measurement models**

The value measurement models include the Analytic Hierarchy Process (AHP), the Multi Attribute Utility Theory (MAUT) and other approaches where the alternatives are compared using a numerical scale in order to obtain a final order of merit of the alternatives.

The Analytic Hierarchy Process (AHP)[27] is widely used in energy planning (Pohekar and Ramachandran, 2004 and Huang et al., 1995). Akash et al. (1999) used this process to compare different electricity power production options in Jordan. The cost criteria included fuel, hardware cost, maintenance and service, auxiliary system, and environmental constraints. The benefit criteria were the efficiency of the system, its reliability, its safety, availability of the fuel used in the system, its effect on the national economy, and social benefits. The authors concluded that renewable systems were the best choice with the lower cost-to-benefit ratio. More recently, Nigim et al. (2004) proposed AHP to aid communities in prioritising local viable renewable energy sources in the Waterloo Region in Canada. The authors considered in their analysis, criteria like the availability of the resources along with technical, financial, environmental and social aspects. A group of stakeholders[28] was involved on the definition of the criteria and on the pairwise

[27] A detailed description of the AHP method may be found in Saaty (1980) or Rogers (2001). In chapter VI of this work additional insights to this model are also given.
[28] By stakeholders we refer to any agency, group of people, or individuals that are affected by, or have an interest in the decision under analysis.

comparison of the alternatives.

Poekar and Ramachandran (2004) observed that the Multi Attribute Utility Theory (MAUT)[29] is not frequently used for energy planning, and only a few studies used this method after 1990. This may be due to the complex requirements of the process in explicitly formulating utility functions. An example where it is used is the study by Pan et al. (2000), where the authors present an extended MAUT and apply the method to a sample case study, concerning the evaluation of electric utility long-range generation expansion strategies. Also Voropai and Ivanova (2002) suggest an approach based on the utility theory for the analysis of the expansion options of large electric power systems.

Almeida et al. (2005) developed an additive value function for evaluating 14 new medium and large hydropower projects in the centre region of Portugal. The authors considered several positive and negative impacts including for example energy output, water value, socio-economic development and environment. The final output was the global ranking of the projects according to the established weights and scores of each project under each criterion.

When comparing electricity generating alternatives, authors frequently rely on the monetary valuation of the impacts. The alternatives may then be compared and ranked based on a single cost value integrating financial and external costs. The ExternE project is a well known approach aimed to value in monetary terms the external costs of energy related activities[30]. The results of this project have been extensively used in energy planning and in particular in the discrete evaluation of electricity generation technologies (see different examples of application in Klaassen and Riahi, 2007; El-Kordy et al., 2002; Rajaf and Kypreos, 2007 or Krewitt, 2002). Also based on ExternE results, Saleiro et al. (2007) presented a comparison of wind power costs and CCGT costs for Portugal. Both projects were analysed independently using the levelised electricity generation cost[31] for the final comparison. However, the study does not include aspects like additional grid cost or the low capacity credit of wind.

[29] A detailed description of these methods may be found in Keeney and Raiffa (1976).
[30] The ExternE project is longer debated in Chapter IV.
[31] The levelised lifetime cost (€/kWh) is the ratio between the present value of the total lifetime expenditures versus the expected total lifetime electricity outcome. A description of this method may be found in IEA/NEA (2005).

Dale et al. (2004) compared the total cost of a large scale wind scenario in the UK with a conventional scenario where a similar amount of energy is generated by gas-fired plants only. The analysis comprised investment, fuel and O&M and network cost. The authors included also an estimation of the extra balancing cost due to the increase part-loaded of the reserve plants and the extra capacity needed for large wind power scenarios. No assumptions were made on the emissions of each alternative; as such the analysis relied exclusively on the financial valuation of each project. On the other hand, Bergmann et al. (2006) focused only on valuing the external costs and benefits of renewable technologies in Scotland. The attributes considered included aspects like landscape impact, air pollution or increase in electricity bill. The final output of the study was the welfare change of each of four renewable energy projects considered comparatively to the base case of fossil fuel power expansion.

- **Outranking methods**

Outranking models were used in many studies for electricity planning, relying mainly on ELECTRE and PROMETHEE methods[32] (Lϕken, 2007). Outranking methods focus on pairwise comparisons of alternatives where the starting point is a decision matrix describing the performance of the alternatives to be evaluated with respect to identified criteria (Palma et al., 2007). The alternatives are then ranked according to the degree of dominance of one alternative over another, based on a preference function (PROMETHEE) or based on concordance, discordance indices (ELECTRE). The final output is the proposal of the best alternative or a preference ranking of the alternatives.

Among many others, some examples include, Georgopoulou, et al. (1997) who proposed the ELECTRE III method to select different exploitation options of renewable energy sources together with more conventional solutions for a Greek island. The evaluation criteria included a large set of elements related to economic issues, security of the system, environmental and social aspects. Some of these criteria, such as cost or quantity of fuel used were measured on quantitative scales, while others, such as stability of the network or visual amenity were valued under a qualitative impact scale. For the classification, individuals representing particular groups were called to give their insights. Also Beccali et

[32] A detailed description of these methods may be found in Vincke (1992) or Figueira et al. (2004).

al. (2003) proposed ELECTRE III for the selection of the most suitable renewable energy technologies for the Sardinia region, taking into consideration political, economic, technical and environmental aspects.

Topcu and Ulengin (2004) used PROMETHEE for the evaluation of different electricity resources, including renewable, nuclear and fossil fuel power plants. The possible resources were evaluated based on physical, environmental, economic, and political aspects. Also Haralambopoulos and Polatidis (2003) describe a framework to achieve group consensus in renewable energy projects based on PROMETHEE II. The framework was applied in selecting geothermal development scenarios and the investigation included economic and environmental criteria using quantitative and qualitative scales. More recently Diakoulaki and Karangelis (2007) evaluated four scenarios for the expansion of the Greek electricity system using both the PROMETHEE method and cost benefit analysis and considering economic, technical and environmental criteria. For the PROMETHEE method, and in order to check the rankings' sensitivity to the varying preferences of the concerned stakeholders, the authors assigned different sets of weights to each criterion. To apply the cost–benefit methodology, the criteria performances were translated into monetary terms.

Goletsis et al. (2003) analysed a large number of project proposals for the Armenian energy sector. The prioritisation of project proposals was achieved through the use of a multicriteria ranking method combining ELECTRE III and PROMETHEE. Also Mavrotas and Diakoulaki (2003) proposed the combination of two tools (ELECTRE and integer programming) to handle the problem of allocating wind parks in a Greek prefecture.

A different approach to an energy decision making problem, also relying on value measurement of different alternatives, was presented by Cavallaro and Ciraolo (2007). The authors used scenario analysis to assess the feasibility of installing wind turbines in an Italian island. The solutions proposed were described according to economic, technical and environmental criteria where impacts on ecosystems and on social acceptability were also included as qualitative variables. Using the NAIADE method developed by Munda (1995)[33], based on comparing pairs of alternatives and using preference relations, a final order of merit of the alternatives was obtained.

[33] An introduction to this method may be found in http://alba.jrc.it/ulysses/voyage-home/naiade/naiahome.htm.

Based on the examples presented above, Figure 3.4 describes the general framework for energy planning with discrete evaluation of the alternatives.

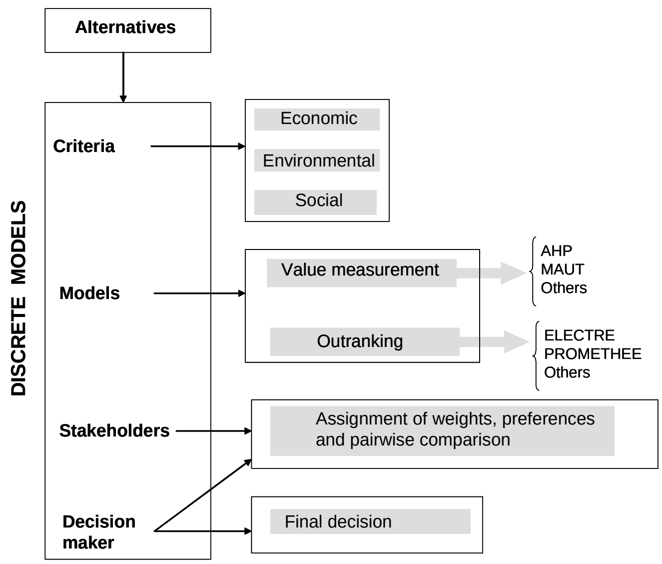

Figure 3.4- Energy planning with discrete models.

The studies based on discrete methods start by identifying a number of possible energy plans or strategies. These plans are then characterised according to a set of criteria and different methods may be used to aggregate all the information in a final ranking of the available alternatives. The models often deal with the economic, environmental and social dimensions of the problem. Depending on the model used, a final score may be obtained for each alternative either dimensionless or with monetary translation or the final output may be the preference ranking of the alternatives or the proposal of the best alternative. Discrete models often call for the stakeholders and/or the decision maker involvement throughout the process to assign weights, to indicate preferences or to participate in pairwise comparisons.

Discrete methods have the advantage of presenting to the decision maker a set of detailed characterised alternatives, which may make the decision process clearer than when complex mathematical functions are involved. Also, these methods have the ability to include both quantitative and qualitative criteria in the same framework. Methods like AHP or outranking are claimed to be simple and easy to understand (Lϕken, 2007). However, energy problems are frequently very complex involving a large number of alternatives and criteria, which represents an important drawback to these methods.

In the case of electricity power planning, the large number of possible mixes of electricity generation technologies gives rise to an extensive number of alternatives, thus requiring special attention on the selection of the feasible electricity plans to be analysed under discrete methods. These alternatives frequently come from government organisations or from the company in charge of the management of the electricity system, may be proposed by experts or stakeholders or may be developed by the researcher taking into account the specific characteristics of the electricity system under analysis.

III.4.3 Summary of the models reviewed

Table 3.1 summarises the characteristics of the single and multiobjective programming models and discrete models reviewed in the later sections.

Table 3.1- Single and multiobjective programming models and discrete models for energy planning. (Source: adapted from Malczewski, 1999)

Characteristics	Programming models	Discrete models
Criteria defined by	Objectives	Attributes
Objectives defined	Explicitly	Implicitly
Attributes defined	Implicitly	Explicitly
Constraints defined	Explicitly	Implicitly
Alternatives defined	Implicitly	Explicitly
Number of alternatives	Infinite (large)	Finite (small)
Relevant to	Design/search	Evaluation/choice
Criteria included	Economic, environmental	Economic, environmental and social
Participative approach	Decision maker	Stakeholders/decision maker

The programming models define the objectives and constraints explicitly using mathematical functions. The alternatives and attributes of these alternatives against each criterion are defined implicitly by the set of constraints. On the other hand, the discrete models define a finite number of alternatives and their attributes explicitly, but the objectives and constraints are not explicitly reported. Single and multiobjective programming models are particularly relevant on the design and search of optimal energy plans. As for discrete models, they are mainly used for the evaluation and selection of a limited number of energy plans. The literature review above has highlighted several points. First, optimisation models usually focus on economic and environmental impacts criteria but social impacts are not usually integrated in the models. Second, discrete models may include qualitative and quantitative criteria accommodating frequently the three dimensions: economic, environmental and social. Third, optimisation models rely mainly on a restricted number of decision makers for the assignment of goals or weights to different objectives while discrete models frequently involve stakeholders from multiple groups in the evaluation process. Finally, both single and multiobjective programming models and discrete models can be used in participative approaches.

III.4.4 Criteria assessment: Monetisation and multicriteria methods

The methodologies for addressing external costs and benefits can be divided into two broad categories: monetisation of all criteria and multicriteria decision making methods.

The aim of valuation of externalities (monetisation) is to achieve an economically efficient allocation of resources through the integration of externalities into the energy price (Kim, 2007). It is therefore necessary to estimate damages, to assess their importance and to place monetary values on non-market goods.

The externality evaluation of different power generation technologies has been addressed by several researchers and institutions including Rowe et al. (1996), Roth and Ambs (2004) and the well recognised ExternE project (European Commission, 1995a). Kim (2007) reviews some of these studies and presents a summary of the values found for the external costs. The results reveal a large disparity of values, due to methodology differences, the diverse technologies considered and the specific characteristics of the proposed implementation site. This finding corroborates Kannan et al.’s (2007) opinion that a reliable externality cost estimate is not yet established and the process of internalising them in any evaluation is difficult and open to question. However, there seems to be agreement that fossil fuels (especially coal and oil) and nuclear power present the largest external damages, while damages from renewables are lower.

Söderholm and Sundqvist (2003) discussed the limitations of the economic valuation of environmental impacts, arguing that, although frequently providing relevant and reliable information for policy makers, environmental valuation based on welfare economic theory gives only partial insight into many environmental issues. The authors recall in particular that environmental issues often have a broad ethical content and people tend to possess different preference structures. In general, there is a need to combine analyses based on intensive value structuring, involving focus groups and surveys from large numbers of people. Studies may involve monetary valuation, but should also include a strong focus on the ethical values held by the respondent. The authors conclude that: “The usefulness of economics in making rational choices over limited resources is vital, but in the environment and energy field it must be complemented by other forms of social intelligence about what should be the important criteria in social choice.”

The explicit monetisation of the impacts has the advantage of being based on well developed economic theory as it represents the value of the good to the public in general. The method can be used in other studies and it promotes consistent evaluation of different projects (Hobbs and Meier, 2003). Additionally it has the advantage of providing results on a scale compatible with the market mechanism and more comprehensible to decision makers (Diakoulaki and Karangelis, 2007). However, as pointed out above, there are some major drawbacks, namely: the basic economic assumptions are not universally accepted, fundamental value judgments are made by analysts and may involve complex tasks with methods difficult to apply in practice (Hobbs and Meier, 2003).

Hobbs and Meier (2003) recommend emphasising the monetisation process when environmental costs are straightforward to compute (e.g. CO_2 allowances), defensible monetary estimation of damages exists or there is a need for uniformity of the value judgments. Controversial aspects, like the economic valuation of human life should be avoided. Also Goletsis et al. (2003) argue that monetisation is not easy and consensus is not easily achieved when fundamental value judgments have to be made. Studies such as ExternE address the monetisation of external impacts and even include the more controversial aspects, but the monetisation process is still insensitive to individual preferences. Although an attempt is made to take into consideration the subjective nature of the opinions, the process assumes the generalisation of judgments. External costs are assigned to each technology, regardless of the specific characteristics of the system in question and of local people judgment. Energy projects, although having global impacts are generally site specific and external values derived for one project may not be suitable for a similar projects located in a different area.

Even in regard to CO_2 values, the market value should not be assumed as a direct reflex of the society concerns on climate change. It is worth recalling that the market cost of CO_2

reflects only a pure financial cost based on the transaction of allowances between producers who emit less than their allocation and producers that exceed their allocation and need to buy the certificates. This market value must be included in the cost function of the model as a new variable cost of financial nature, but the total environmental impact should also be included and measured as an independent criterion for decision making, expressed in physical units. In the same way the social impacts of the decision must be assessed for each particular system, taking into consideration the merits and drawbacks of a specific project and the different values and preferences of the stakeholders involved, with particular attention given to the local communities.

The multicriteria approach does not resort to the determination of monetary values of the damages caused by environmental disruption, advocating that resource allocation can not be left to free markets and consumer choice (Kim, 2007). Works like Lϕken (2007) or Pohekar and Ramachandran (2004) demonstrate the popularity of the various multicriteria methods in energy planning problems. Haralambopoulos and Polatidis (2003) reinforce the view that the complexity of energy planning, involving multiple conflicting factors and different groups of decision makers, makes muticriteria analysis a valuable tool in the decision making process.

According to Hobbs and Meier (2003) multicriteria decision making presents some major advantages over the monetisation process: the participation of the users is emphasised, tradeoffs are explicit, values are obtained with the direct collaboration of stakeholders and worst alternatives are easily ruled out. However, the process may be difficult to understand creating problems in regard to the stakeholders' collaboration and results are difficult to repeat or verify. These methods are especially useful for analysing unique site specific projects, or when conflict on fundamental values exists among stakeholders or even when no monetary value estimation exists for the social costs. As Diakoulaki et la. (2005) state "Multicriteria methodologies provide a combination of quantitative and qualitative approaches, and create decision platforms allowing for rationality to be merged with subjective judgements and ethical concerns".

Hobbs and Meier (2003), advocate that neither monetization nor muticriteria decision making is unambiguously superior to the other but rather have complementary strengths. Frequently the best approach to a problem is the combination of the two methods. The same way, Söderholm and Sundqvist (2003) argue that pricing of power-generation externalities must be balanced with other approaches that include a strong focus on the ethical values held by public in general and focus groups.

III.4.5 Public involvement in energy decisions

Energy planning often involves many decision makers and can affect numerous and heterogeneous stakeholders, with different value systems and different concerns (Greening and Bernow, 2004). Due to the great variety of ethical positions, the perception of the stakeholders involved may differ significantly. The consultation of relevant experts and competent authorities is an essential element in the decision process and multicriteria applications often involve a large and interdisciplinary group of stakeholders (Diakoulaki et al. 2005). There are many examples in the recent literature, demonstrating the importance of integration of experts, stakeholders and public in general in energy decision making.

The World Commission on Dams (2001) underlines the need to implement participatory decision-making for improving the outcome of dams and water development projects. According to this report, gaining public acceptance is a strategic priority. In order to develop water and energy resources in an equitable and sustainable manner, it is essential that there is public acceptance of such initiatives. Stakeholders should be actively involved from the start and party to the negotiation of project-specific agreements on issues such as benefit sharing, resettlement and compensation.

Wolsink (2007) gathered data on public attitude towards wind power from several studies. He drew attention to the need to take into consideration public attitude on wind implementation decisions, not only at a general level but also at the local project level and stressed the importance of including the public in the decision making process. Also, according to Shackley et al. (2005), public perceptions can have a very significant and frequently unanticipated effect upon major planned projects.

Del Río and Burguillo (2007) stressed the importance of the participatory approach which takes into account the opinions and interests of all stakeholders. The authors argued that the assessment of a project's sustainability should focus not only on the impact of the proposal, but also on how this impact is perceived by the local population, how the benefits are distributed among the different players and how this perception and distribution affects the acceptance of the project. In conclusion, the acceptance or rejection of a renewable energy project by the local population can make its implementation and its contribution to local sustainability either a success or a failure. Loring (2007) analysed the factors affecting wind energy projects success in England, Wales and Denmark and concluded that that projects with high levels of participatory planning are more likely to be publicly accepted and successful.

Although the advantages of involving the public in the decision process are well documented, their effective participation may be a difficult task. Participatory processes are costly and time consuming and are not yet very common in the public and private sector. In most applications, stakeholders participate mainly in the assignment of weights. However, there are some examples of stakeholders' involvement in the elaboration of the alternatives and a few of their involvement in all major stages of the decision process (Diakoulaki et. al, 2005).

Haralambopoulos and Polatidis (2003) propose the inclusion of a group of stakeholders in the selection of renewable energy projects, which would assign weights to criteria. Although the authors identified the relevant groups of stakeholders, their effective participation was not achieved in the reported study. For ranking large hydropower projects, Almeida et al. (2005) used weights previously assigned to each impact by a group of experts. The authors do not detail the consultation and agreement process on the basis of the definition of those weights. Shackley and McLachlan (2006) examined the responses of stakeholders from the public and private sectors to future energy scenarios. The stakeholders were involved in the evaluation phase, scoring each of the scenarios against criteria previously developed by the project team.

Nigim et al. (2004) included the focus community group not only in the evaluation process but also in the elaboration of the appraisal criteria for adopting renewable energy sources. Polatidis and Haralambopoulos (2007) describe an evaluation process applied to a proposed wind farm proposed in Greece, where stakeholders participated in what the authors called the decomposition analysis of the project, including the impact assessment on the dimensions of sustainability, namely economy, environment, society and resource base. Weights elicitation procedures have been applied to assess the stakeholders' preferences between the criteria.

In other studies, the participation of stakeholders is not restricted to the final evaluation and selection of the criteria. Hobbs and Meier (2003) describe a multicriteria process followed at British Colombia Hydro to assist in the preparation of the 1995 Integrated Electricity Plan. A group of stakeholders was selected and participated in several phases of the process including the definition of the objectives and alternatives and the evaluation of the plans. Integrated frameworks, involving the stakeholders in several stages of the energy planning process, are also presented by Georgopoulou et. al. (1997) and Georgopoulou et. al. (1998). The proposed processes started out with the definition of energy strategies, reflecting the main attitudes of the players involved. The selection of criteria was decided together with the stakeholders in an attempt to ensure that all the main points of view were reflected in the criteria set. Finally the stakeholders also participated in the evaluation of the alternatives assigning weights of relative importance to these criteria. In Goletsis et al.'s (2003) study, individuals of relevant organisations and experts participated in the identification of alternative energy projects. Four decision makers collaborated in the definition of the ranking criteria and in the weighting process. At the final stage, the authors addressed the issue of the assessment of group consensus and proposed tools to support consensus reaching.

III.5 Renewable energy sources and electricity planning

The share of renewable energy sources is expected to increase greatly in the future, in particular in respect to the electricity production sector. This increasing contribution to energy supply rises questions such as: what will be the effect on final consumer prices? what will be the environmental gains? to what extent are the renewable technologies able to compete with conventional ones? These issues are extensively debated in the literature, focusing on several renewable technologies and using different approaches, relying on a pure financial analysis or full social costing, on fully integrated systems or single analysis of different technologies.

Dale et al.'s (2004) study for the UK electricity system concluded that if wind power levels were increased and reached 20% of the electricity sales in 2020, the extra unit cost would represent about 5% of the average domestic unit price. This study took into consideration an estimate of the extra balancing costs for large wind scenarios and assumed that the future installation cost for onshore and offshore wind power plants would be lower than the present values. No external costs were considered in the analysis. The authors identified the investment cost of wind turbines as the greatest uncertainty in terms of the cost difference between the wind and a conventional scenario, based on new CCGT capacity.

The screening curve[34] analysis by Kennedy (2005) for Long Island, USA, calculated the social benefit of offshore wind power over advanced fossil fuel technologies and concluded that it is never positive and exhibits a diminishing pattern with increasing penetration. The social benefits were based on environmental cost (CO_2 and other emission damages), energy cost (variable O&M[35] and fuel costs) and capacity cost (fixed O&M and installed capital costs) factors. This work demonstrated that wind power has a significant influence on the capacity requirements and dispatching of other plants and that the planner should not assume that new wind power simply displaces one plan type or another.

Similar results were obtained in another study conducted in the USA, but now focused on Texas. Dobesova et al. (2005) estimated the private and social costs of wind generation and compared these with the cost of fossil generation, accounting for the pollution and CO_2 emissions. The authors concluded that the pollution reductions and lower CO_2 emissions obtained with wind could be attained at about the same cost using pulverised coal or natural gas combined cycle plants with carbon capture and storage, or even more economically with an integrated coal gasification combined cycle plant with carbon capture and storage.

Other authors obtained very different results. Miragedis et al. (2000) compared possible electricity expansion plans, each assuming different degrees of renewable energy penetration. A comparison of the private and full social cost (private and external costs) of the alternatives led to the conclusion that social costing may completely reverse the economic attractiveness of the alternatives, as determined on the basis of private costs. According to the results, the private cost of renewable intensive plans is higher than the conventional plans. On the other hand, the higher the penetration of renewable energy

[34] Screening curves plot the average cost of maintaining and operating a generator against the generator's load factor, allowing for comparing the relative economies of different plant types. A full description of the method may be found in Kennedy (2005).
[35] O&M- Operations and maintenance.

sources, the lower the cost imposed on society as a whole. Thus, the authors conclude that not taking into consideration the external costs associated with electricity generation favours conventionally generated electricity.

Kannan et al. (2005) compared life cycle cost of centralised and distributed power generation technologies in Singapore. The final output of the analysis indicated that power generation from clean/renewable power generation technologies is costlier than fossil fuel based power generation. However, the author notes that low environmental impacts can compensate for unfavourable economics, if environmental externalities become an accepted paradigm in the appraisal.

A study by Islas et al. (2004) analysed the CO_2 mitigation costs of a scenario in which electricity generation was based on renewable energy technologies, measured against a conventional scenario based on natural gas technologies. The CO_2 mitigation cost was based on cost and benefit estimates expressed in present value, and in the CO_2 emissions reduction derived from the comparison between the scenarios. The authors concluded that without considering the hypothesis of future capital cost reduction of the generation technologies (technological progress), the CO_2 mitigation cost of the renewable scenario was always higher than the conventional scenario. This situation would only be changed when the hypothesis of technological progress was included and there was an increasing trend on natural gas cost. However, in this study only the costs of capital, operation and maintenance and fuel expenses were considered and no estimation of the external costs was included.

El-Kordy et al. (2002) presented a full analysis of the cost of electricity generated from renewable (wind and photovoltaic) and non renewable technologies. The authors did not analyse electricity generation plans or scenarios, but rather focused on the independent comparison of the technologies. Considering external costs, the wind power technology is found to be the most interesting technology. If external costs are not included in the analysis, other conventional technologies, namely CCGT, present lower life cycle costs. Similar results were obtained for Portugal, when comparing wind power costs with CCGT: CCGT is still more attractive than the wind energy when only financial aspects are accounted for, but when external costs are considered the results may change, depending on the values assigned to externalities (Saleiro et al., 2007).

In 1998, the results of an investigation with reference to the Danish electricity system indicated that from the socio-economic perspective wind power and natural gas were equal and that wind power was more advantageous than coal-fired power plants, taking into consideration financial and external costs and including also back-up costs for the wind power option (Munksgaard and Larsen, 1997). More recently, Owen (2006) reported that coal and gas exhibit a clear absolute cost advantage over the bulk of renewable technologies, although electricity wind power can approach similar cost levels. The author concluded that external cost, if internalised into the price of the resulting output of electricity, could clearly lead to a number of renewable technologies being financially competitive with generation from coal plants but not yet with CCGT.

Another recent study by Moran and Sherrington (2007), used cost–benefit analysis to assess the economic feasibility of a large scale wind farm project, taking into account positive and negative externalities of generation and also de value of the CO_2 avoided emissions. This project was compared with a CCGT plant. The results indicate that the wind power project returns a positive net present value, thus suggesting the wind farm delivers a net welfare gain to society. Even when negative aspects frequently associated with wind farms, such as visual and noise disamenity or the extra balancing costs to the grid, are quantified and included the project still presents a positive output. This result is strongly influenced by the natural gas price values, which were based on trend forecasts of recently very high gas prices.

Obviously the conclusions drawn by each author strongly depend on the assumed costs for each technology, in particular in regard to the investment and fuel costs. Regardless of the approaches used in the studies and even taking into consideration these differences, most of the results suggest that in general the strict financial in contrast to full social costing of the electricity generation options may easily lead to opposite conclusions. If the energy planning is based on the private cost figures most renewable energy sources cannot compete with conventional fossil fuel technologies. However, the lower environmental impacts of renewable energy technologies can compensate for their estimated higher financial costs.

Notwithstanding, some renewable technologies and wind in particular, are becoming economically interesting even on pure financial grounds due to aspects such as the inclusion of CO_2 allowances market cost, their technological development and especially due to the increase of natural gas prices. Wind power competitiveness may increase even more, if instead of considering the market value of CO_2, the cost of CO_2 brought to society is fully accounted and all other external costs are also integrated in the analyses.

The underlining assumptions of the models influence the magnitude of estimated costs and the assessment of the role that renewable energy sources may have in future electricity systems. Aspects like the technologies selected for comparison, their estimated investment cost, the fuel costs and the inclusion of external costs in the analysis are key elements for determining the RES benefits. In addition, assuming that one renewable energy technology will displace one conventional plant type or another, is not a straightforward procedure. As Kennedy (2005) demonstrated, installing new renewable power plants encourages the reallocation of capacity and output among different generator options setting a new equilibrium. Thus, the cost and benefits should be assessed by an integrated planning process of the overall system, rather than by direct comparison of technologies.

III.6 Concluding remarks

The literature review presented here, although far from being exhaustive, illustrates the diversity of approaches used by authors when addressing issues related to energy decisions. A much more extensive analysis of the subject may be found in studies like Lϕken (2007) or Pohekar and Ramachandran (2004) where the authors review a large number of publications on the use of multicriteria decision making for energy planning. Also Hobbs and Meier (2003) present what they call a “representative sample” of multicriteria decision making applications to energy planning and policy problems. Huang et al. (1995), present a comprehensive literature review on decision analysis on energy and environmental modelling, including studies published from 1960 to 1994. Greening and Bernow (2004) collect some examples describing the application of several multicriteria methods to energy and environmental issues. Diakoulaki et al. (2005) analysed a large number of publications addressing the use of multicriteria methods to energy related decisions and Jebaraj and Iniyan (2006) review several energy models including planning and optimisation models among others.

Although studies like Greening and Bernow (2004) support the supremacy of multicritera tools over the traditional cost benefit analysis (based on the monetary valuation of all internal and external costs), the monetisation of external cost and benefits is extensively used in the literature. Mirasgedis and Diakoulaki's (1997) comparison of both approaches on the evaluation of electricity generation options demonstrates the affinities of both methodologies and reveals that the differences rely mainly on the way weights are assigned to impacts: in the case of monetary valuations the weights are based on collective and scientific view and in the case of multicriteria methods the weights are based on more subjective opinions. In fact, most of the energy planning studies reviewed did not conclude on the superiority of one method over others. On the contrary, there seems to be generalised agreement that the combination of one or more of the available techniques is frequently the best approach. Hobbs and Meier (2003) and Lϕken (2007) advocate that a combination of two or more methods may be favourable, making use of the different methods' strengths.

Designing a sustainable energy plan implies addressing and integrating technical, environmental, economic and social dimensions. The participation of the public, stakeholders and experts is now generally accepted as a core element of the whole decision process. The use of multicriteria tools allows for the description and evaluation of the energy planning problem in its many dimensions and assists in the assignment of relevance to the different aspects of the problem (Greening and Bernow, 2004). The proper translation of all relevant costs is also a fundamental aspect of the formulation of the energy planning problem. The creation of new markets, as for CO_2 allowances, leads to the need to accommodate new variables in traditional cost functions.

Formulating a unique optimal energy plan is unlikely to be a realistic objective. Upham and Shackley (2006a and b) recognise the importance of participatory methods for more widely accepted outcomes, but also underline that they will not avoid the need for difficult and contentious decisions to be made. Bringing Lahdelma et al. (2000) views on environmental planning into the electricity planning field, it may be stated that the complexity and dimension of the process and the need to consider divergent points of view of the decision makers implies that objectively an ideal solution does not generally exist, and the planning process can be characterised as a search for acceptable compromise solutions.

As Munda (2004) recalls: "The world is characterized by deep complexity (…) one may decide to adopt a reductionistic approach trying to tackle only one of the many possible dimensions or simply to deal with the real world complexity". The energy decision making is a clear example of this complexity, being multidisciplinary and with strong social implications. The process usually involves several steps including the characterisation of the energy system under analysis; the identification of the possible technologies; the choice of the evaluating criteria; the selection and inclusion of the social players including those able to choose or to influence decisions and those affected directly or indirectly by these decisions; and the generation of an evaluation tool able to incorporate all these criteria and stakeholders opinions.

The deregulation of the electricity market created the need to deal with additional sources of uncertainty, focusing on the electricity planning at company level. According to the Portuguese legal framework, new power plants must comply with central plans to gain approval for construction and operation. Decree-Law 29/2006 states that: "The exercise of electricity production activities is free, but subject to obtaining a licence from the administrative authorities." The general decision criteria for evaluating a licence for electricity production activity include among others: the contribution to the energy policy National objectives, the contribution to the environmental policy National objectives and the contribution to the safety and flexibility of operation of the electricity system (Decree-Law 172/2006). Thus, the output of central planning in Portugal is still an important tool for guiding private companies' investment strategies. But as Dyner and Larsen (2001) highlighted, this output should be seen essentially as benchmarking for the creation of possible scenarios, since the uncertainty of the sector leads to rapid changes on the priority assigned to each technology[36].

Sustainable development goal requires dealing with electricity planning as a multidimensional process where value judgments must be integrated and all the impacts of the electricity generation technologies are fully acknowledged. The energy planner must recognise the need to involve a large number of players in the process, tradeoffs among conflicting objectives must be made and a wide range of options must be considered. After the identification of the technological options, these must then be analysed not only from

[36] This uncertainty is evident when comparing REN (2003) and REN (2005) investment plans. The first report assumed an evolution of the large thermal power sector based only on new gas fired plants. The second report, assumed a different position proposing an increase of both gas and coal generation capacity for Portugal.

the cost perspective but also from the social and environmental points of view. The next chapter follows with a review of the social and environmental impacts of the electricity generation technologies.

CHAPTER IV

ENVIRONMENTAL AND SOCIAL IMPACTS OF THE ELECTRICITY PRODUCTION TECHNOLOGIES

This chapter discusses the main environmental and social impacts of the electricity production technologies. Although renewable energy sources are generally associated with lower external impacts comparatively to fossil fuel fired plants, they are not absolutely impact free. In regard to wind power, impacts on human amenity and on the ecosystem can be relevant along with the effects on the power system operation.

IV.1 Introduction

The production and use of energy have environmental and social consequences at local, regional, and global levels. These impacts extend throughout the fuel cycle of an energy system and can manifest themselves over short, medium or long time-scales (UNDP, 2000). As concluded in the previous chapter, the proper evaluation of these impacts and its inclusion on the energy decision making process is fundamental to ensure a sustainable energy sector.

Local impacts, although affecting a small group of people may be of extreme importance, particularly if involving occupational disease and accidents that affect workers or members of the public. Local impacts are also more relevant for renewable technologies. For example, most concern over the development of wind farms typically relates to visual intrusion in natural landscapes and to noise emissions (European Commission, 1998). However, large thermal power plants, whether they use renewables or fossil fuels, can also have adverse local resource impacts related to excessive water consumption, soil and ground-water pollution, or deforestation. The United Nations Development Program (UNDP) report on sustainable energy strategies presents some examples of regional impacts related with energy production such as: acid deposition, habitat destruction, large scale displacement of people due to the construction and operation of large hydro projects or radiation due to nuclear power plant accidents (UNDP, 2000). At global level, the link between energy and the worldwide global warming effect is well documented. Other global relevant impacts include the loss of biodiversity and land degradation.

The European Commission (1998) maintains that impacts should be assessed over their life times. Although, this introduces a good deal of uncertainty for long term impacts, such as those of global warming or high level radioactive waste disposal, to ignore them might suggest that they are unlikely to be of any importance. In the same way, Weisser (2007) recalls that in economies where carbon is being priced or greenhouse gas emissions (GHG) constrained, not properly accounting for the life-cycle GHG emission of electricity generation, may provide an advantage to technologies with trans-boundary upstream emissions over technologies without significant life-cycle emissions arising outside the legislative boundaries of greenhouse gas mitigation policies.

This Chapter analyses the impacts of the different electricity production technologies based on a literature review. Section IV.2 focuses on the close relationship between energy and environment; it details the trends of CO_2 emissions[37] from primary energy consumption and from electricity production activities, and outlines the Kyoto protocol and the European Union (EU) regulation for promoting environmental performance of the energy sector. The impacts of electricity generation activity are described in Section IV.3 for both fossil fuel and renewable energy technologies. This section addresses with particular detail the social and ecological impacts of wind power, discusses the effects of its integration on the power system and reviews studies on the social acceptance of this technology. Section IV.4 closes with the formulation of a general framework for sustainable electricity planning and concluding remarks.

IV.2 Energy and the environment

Energy production and consumption is strongly linked with the environmental pressure on the planet. For example, the emissions of SO_2 (Sulphur Dioxide), CO_2 and other greenhouse gases and NO_x (Nitrogenous Oxides) for a certain period, depend on the amount of electricity produced and on the technological mix of the power plants operating in each electricity system during that period. The shares of each fossil fuel, nuclear and renewable plants operating along with the efficiency of each unit and cleaning mechanisms available are key factors to assess the environmental performance of the electricity system and of the country.

According to the European Environment Agency report (EEA, 2006) for the EU-25, the main factors responsible for reducing CO_2 emissions derived from electricity and heat generation systems are improvement in efficiency, fuel switching from coal to gas and, to a much lesser extent, increase in the share of renewables. Portugal, however, represents a particular case where the CO_2 emissions depend heavily on the rainfall conditions. The emissions level shows significant variations related to the pronounced fluctuations of hydroelectric power generation, which is highly dependent on annual precipitation. Nevertheless, the close relationship between energy consumption and the energy sector's

[37] There are 6 greenhouse gases recognised under the Kyoto protocol. The analysis conducted focuses mainly on CO_2. This is the most important anthropogenic greenhouse gas representing 82% of the total greenhouse gas emissions of the EU-27 and 79% of the Portuguese greenhouse gas emissions, in 2005.

CO_2 emissions is evident, as represented in Figure 4.1.

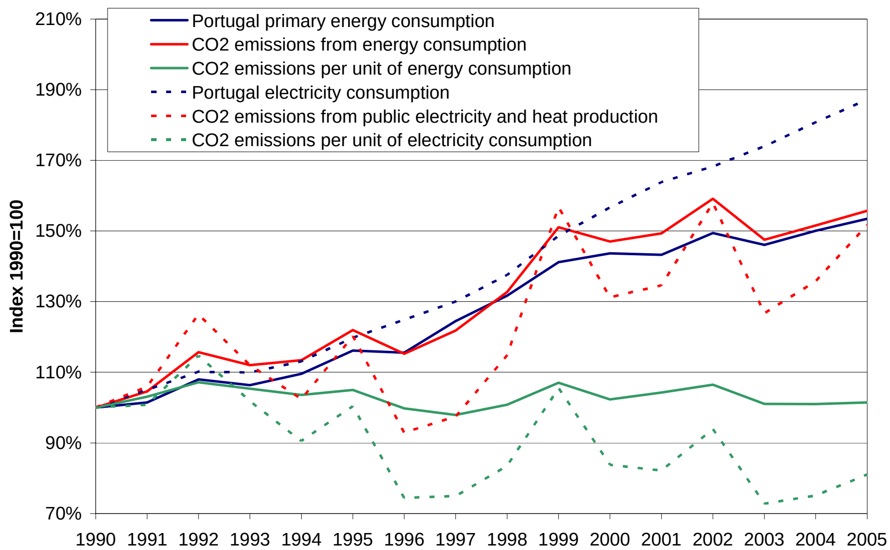

Figure 4.1- Trends in the energy and electricity consumption, in CO_2 emissions and CO_2 emissions intensity in Portugal. Source: Own elaboration of the balances of energy (DGGE site, data drawn in June 2007) and EEA (2007).

After a steady increase in Portugal's CO_2 emissions during the nineties, in recent years the emissions´ growth has been more moderate. The Portuguese National Inventory Report on Greenhouse Gases concludes that these deceleration was due to the introduction of natural gas in the market in 1997, along with the progressive installation of co-generation units and the improvement of the efficiency of industrial processes and of the transportation sector. However, the effect of these measures has been outweighed by the overall increase of energy consumption, which relies mainly on fossil fuel sources (Ferreira V.et al., 2007) and thus CO_2 emissions per unit of energy consumption has remained fairly constant in the period 1990 to 2005.

The Portuguese CO_2 emissions derived from energy consumption present a fluctuating pattern, strongly influenced by the hydropower production. Wet years, like 1997, 2000 or 2003 present better environmental performance than dry years, like 1999 or 2002. This is particularly evident when analysing the CO_2 emissions from public electricity and heat production. It is however interesting to note that the level of CO_2 emissions related to both energy and electricity consumption in 2005, remains close to that of previous years, although this was an extremely dry year. In fact, the low hydropower production was mostly compensated by a move towards low CO_2 options: SRP production, in particular wind power, CCGT production, and also electricity importation.

Figure 4.2, demonstrates the close relationship between energy consumption and CO_2 emissions at a global level. World primary energy consumption is increasing and between 1990 and 2004 grew by 29%. The CO_2 emissions presented a similar trend and by 2004 had increased also about 27% comparatively to 1990. The small difference between the increase rates allowed for a minor decrease on the CO_2 emissions per unit of energy consumed.

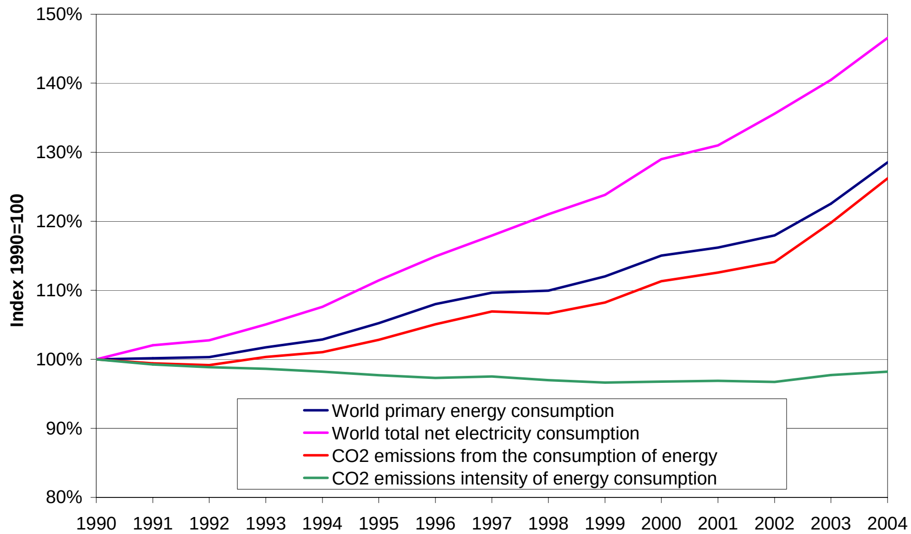

Figure 4.2- Trends in the world energy and electricity consumption, in CO_2 emissions and CO_2 emissions intensity of energy consumption. Source: Source: Own elaboration of Energy Information Administration data. http://www.eia.doe.gov/emeu/international/contents.html (Data drawn in June 2007)

At the European level (EU-15[38]), there is also a general increasing trend of energy consumption, as may be seen in Figure 4.3. However, the use of more efficient and clean technologies along with some structural changes taking place in EU members and the introduction of specific policies and measures, contribute to a less significant increase of CO_2 emissions. As a result, between 1990 and 2005, the CO_2 emissions per unit of energy consumption fell by around 12%.

[38] Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom

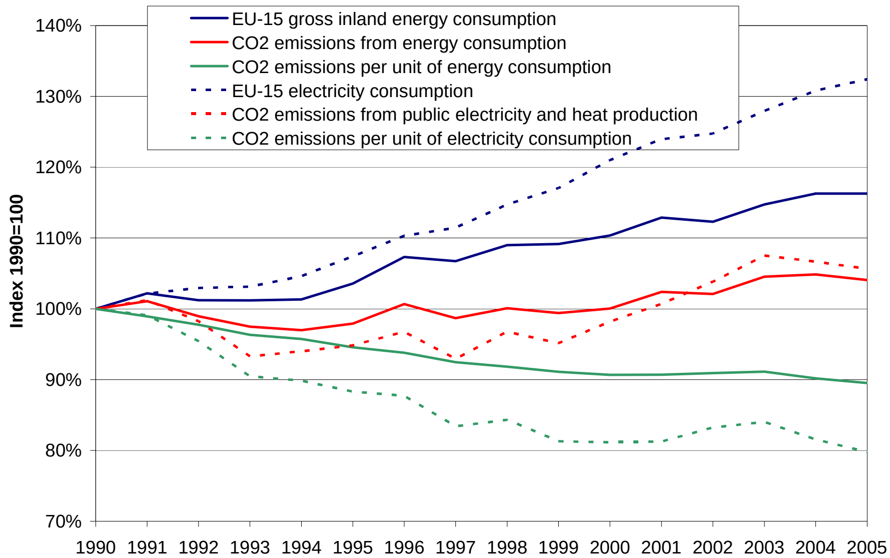

Figure 4.3- Trends in the EU-15 energy and electricity consumption, in CO_2 emissions and CO_2 emissions intensity of energy consumption. Source: Own elaboration of Eurostat data (data drawn in June 2007) and EEA (2007).

The demand for electricity is increasing rapidly and, to some extent, this rising consumption offsets the environmental benefits achieved through technological advances and fuel switching. A similar effect occurs in the transportation sector. Emissions from transport in the EU-15 increased significantly over the same period as a result of a continuous increase in road transport demand. This has offset much of the decrease in other sectors (EEA, 2006). However, in general CO_2 emissions linked to energy and electricity consumption showed a real decreasing trend between 1990 and 2005, indicating a move towards a less carbon intensive fuel mix at the European level.

Energy production and consumption are the largest sources of greenhouse gas (GHG) emissions in the EU. Figure 4.4, shows the 2005 CO_2 emissions produced per sector in Portugal and in the EU-27. About 90% of the total CO_2 emissions in Portugal are energy related, meaning they are result from energy consumption activities. This value rises to 94% at the EU-27 level. Particularly relevant is the role of the electricity and heat production sector. About one third of the CO_2 emissions derive from fossil fuels used for generating electricity, with each power plant capable of emitting several millions of tonnes of CO_2 annually.

Limiting CO_2 concentration in the atmosphere requires the reduction of CO_2 emissions throughout the economic sector. The electricity generation sector has some particular characteristics that make it an important target for CO_2 mitigation, as pointed out by Johnson and Keith (2004): compared to distributed emission sources in the transportation sector, electricity generation plants may achieve deep reductions with minimal impact on energy infrastructures; the centralised ownership and management of the electric utility industry facilitates regulation; generators have gained considerable experience over the last years with increasingly tighter controls on conventional pollutants; and it is not likely the movement of electricity producers to less regulated countries as could happen for the industrial sector.

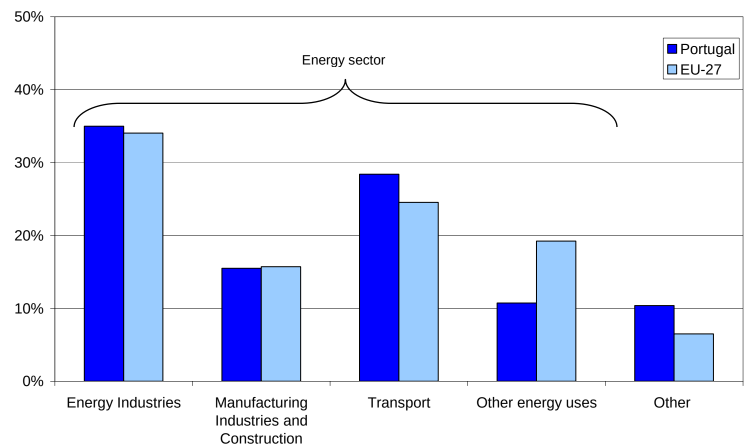

Figure 4.4- Share of CO_2 emissions of air pollutants by activity in 2005, in EU-27 and Portugal. Source: Own elaboration of EEA (2007) data.

In Portugal, the 2005 CO_2 emissions from a coal power plant operation were around 844 g/kWh[39] whereas from a CCGT plant operation this value was close 375 g/kWh[40] . Hondo's (2005) results indicate that even nuclear power plants emit around 24 g CO_2/kWh during their lifecycle, mainly from uranium enrichment, and that wind power facilities account for 29 g CO_2/kWh, mainly released during the construction phase. Renewable energies have in general very low CO_2 emissions and are strongly favoured by environmental regulation for the energy sector.

A key factor in the future development of the energy sector and on the definition of present and future energy policies is the Kyoto protocol, summarised in Figure 4.5. Under the Kyoto Protocol, the EU committed itself to reducing its greenhouse gases emissions by 8% during the first commitment period, from 2008 to 2012. This target is shared between the

[39] Source: EDP(2006a).
[40] Source: Turbogas (2006).

Member States under a legally binding burden-sharing agreement, which sets individual emission targets for each Member State. In particular, Portugal is allowed to increase the average emissions by 27% from the 1990 emission level.

Key aspects of Kyoto protocol[1].

The Convention on Climate Change sets an overall framework for intergovernmental efforts to tackle the challenge posed by climate change. It recognises that the climate system is a shared resource whose stability can be affected by industrial and other emissions of carbon dioxide and other GHG.

The United Nations Framework Convention on Climate Change (UNFCCC) set down the Kyoto Protocol, an international and legally binding agreement to reduce greenhouse gases emissions world wide. This Protocol shares the Convention's objective, principles and institutions, but significantly strengthens the Convention by committing industrialised countries to legally-binding targets to limit or reduce their GHG emissions.

The text of the Protocol to the UNFCCC was adopted at the third session of the Conference of the Parties to the UNFCCC in Kyoto, Japan, on 11 December 1997; it was open for signature from 16 March 1998 to 15 March 1999 and it entered into force on 16 February 2005. The EU and its Member States ratified the Kyoto Protocol in May 2002. As of 6 June 2007, 174 countries and the European Community have deposited instruments of ratifications, accessions, approvals or acceptances of the protocol.

Under the Kyoto Protocol, industrialised countries (Annex 1 countries) are required to reduce the emissions of six greenhouse gases (CO_2, which is the most important one, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride) on average by 5.2 % below the 1990 levels during the first "commitment period" from 2008 to 2012. There are no emission targets for developing countries.

Greenhouse gas emissions are a global problem. This way, the Kyoto protocol authorises three flexible mechanisms to meet the emissions objectives, enabling Parties to make use of lower cost opportunities to reduce emissions, regardless of the place where reductions are achieved:

- ***Joint implementation***: Any Party included in Annex I may transfer to, or acquire from, any other such Party emission reduction units resulting from projects aimed at reducing anthropogenic emissions.
- ***Clean development mechanisms***: It resembles the joint implementation mechanism, but covers reduction projects in developing countries (non Annex 1 countries). The purpose of this mechanism is to assist Parties not included in Annex I in achieving sustainable development and to assist Parties included in Annex I in achieving compliance with their quantified emission limitation.
- ***Emissions trading***: Annex I Parties can acquire units from other Annex I Parties and use them towards meeting their emissions targets under the Kyoto Protocol.

The Protocol encourages governments to cooperate with one another, improve energy efficiency, reform the energy and transportation sectors, promote renewable forms of energy, phase out inappropriate fiscal measures and market imperfections, limit methane emissions from waste management and energy systems, and protect forests and other carbon "sinks".

[1]Souces:
Text of the Kyoto protocol drawn from http://unfccc.int/essential_background/kyoto_protocol/items/1678.php and http://ec.europa.eu/environment/climat/kyoto.htm.

Figure 4.5- Key aspects of the Kyoto protocol.

Directives 2003/87/EC and 2004/101/EC established a scheme for greenhouse gas emission allowance trading in the EU. In January 2005 the European Union Greenhouse Gas Emission Trading Scheme commenced operation as the largest multi-country, multi-sector GHG emission trading scheme in the world[41], creating the European market of emission allowances. CO_2 allowances are now traded in European markets like SENDECO2, APX, EEX, EXAA and NordPool[42].

At the European level, a number of other important measures for promoting environmental performance of energy activities and for complying with the Kyoto Protocol have been adopted. These measures focus on issues like the promotion of energy efficiency (see for example Directive 2006/32/EC on energy end-use efficiency and energy services, Directive 2002/91/EC on the energy performance of buildings and Directive 2003/66/EC with regard to energy labelling of household electric equipment), the promotion of more energy efficient technologies (see for example Directive 2004/8/EC on the promotion of cogeneration or the agreements with car manufactures[43])[44]. Particularly relevant for the electricity generation sector are: Directive 2001/80/EC on the limitation of emissions of certain pollutants into the air from large combustion plants (SO_2, NO_x and dust) and Directive 2001/77/EC on the promotion of electricity produced from renewable energy sources. This last one is described in Figure 4.6.

In addition to these measures, the European Commission has also recently proposed that the European Union commits to cut greenhouse gas emissions by at least 20% by 2020, in particular through energy measures such as: increasing the share of renewable energy in the EU's overall mix, CO_2 capture and storage technologies or more energy efficient buildings, appliances, equipment, industrial processes and transport systems (Commission of the European Communities, 2007a).

Reducing growth in electricity consumption will be crucial from an environmental point of view, especially in relation to consumption of fossil-fuel based electricity. Renewable energy sources produce no (or very little) CO_2, no radioactive wastes and usually significantly low levels of other pollutants. Enhancing the environmental performance of fossil fuel power plants is also fundamental and may be achieved by the increased use of

[41] http://ec.europa.eu/environment/climat/emission.htm

[42] SENDECO2: www.sendeco2.com; APX: http://www.apxgroup.com; EEX: http://www.eex.com/en/; EXAA: http://www.exaa.at/cms/4/ and NordPool: http://www.nordpool.com/.

[43] http://ec.europa.eu/environment/co2/co2_agreements.htm.

[44] A description of the EU legislation in force on energy efficiency may be found in http://ec.europa.eu/energy/demand/legislation/index_en.htm.

effective abatement technologies and efficiency improvements. The need to reduce the pressures imposed on the environment by energy use calls for a continuous and worldwide effort promoting and using cleaner energy sources and technologies, complemented by changes in consumer behaviour.

Key aspects of Directive 2001/77/EC, on the promotion of electricity produced from renewable energy sources in the internal electricity market.

"The community recognises the need to promote renewable energy sources as a priority measure given their exploitation contributes to environmental protection and sustainable development (…) can also create local employment, have a positive impact in social cohesion, contribute to security of supply and make it possible to meet Kyoto targets more quickly."

Global indicative target: The Directive estabelishes the global indicative target of 12% share of renewable energy in gross inland consumption by 2010. In particular it is also estabelished the 22,1 % indicative share of electricity produced from renewable energy sources in total Community electricity consumption by 2010.
National indicative targets: The Directive presents national indicative targets for the contribution of electricity produced from renewable energy sources to gross electricity consumption by 2010. For the Portuguese case, the target is 39%, which corresponds to maintaining the 1997 share as an indicative target for 2010.
Administrative procedures: Member states must take measures aiming to reduce barriers to the increase in electricity production from renewable energy sources, to expedite administrative procedures and to ensure objective, transparent and non-discriminatory rules.
Grid issues: Member states must take measures ensuring that transmission and distribution system operators guarantee the transmission and distribution of electricity produced from renewable energy sources. They may also provide for priority access to the grid system of electricity produced from renewable energy sources.

Figure 4.6- Key aspects of Directive 2001/77/EC.

IV.3 Impacts of electricity generation activity

There is a growing recognition of the importance of the social and environmental impacts of electricity generation activities. As described in the previous chapter, power generation involves a process, in which the actions of the electricity producer may not be appropriately reflected in the market prices of the product. The Energy Information Administration (1995) classifies the externalities attributable to electric power generation in four categories: Air pollutants; GHG; water used and water quality; and land use values.

Clarifying the full costs of power generation for regulators and policy-makers is particularly critical because of the non-differentiation in prices among electricity suppliers generated from different sources with potentially very different pollution emissions and externalities. The basic objective of full social accounting is to make explicit the magnitude of direct environmental costs and other costs derived from electricity production and borne by society, thereby influencing decision-makers towards power sector investment decisions that enhance social welfare (Venema and Barg, 2003).

Developing the defensible estimates of externalities is a complex and costly exercise (Rowe et al., 1996). Externality values for electricity generation were developed in the USA and Europe. Freeman III (1996) and the Energy Information Administration (1995) present some of the major studies providing estimates of the external environmental costs that result from adding capacity to an electricity generation system.

The European Commission together with the US Department of Energy launched a joint research project to assess the environmental externalities of energy use, in 1991. During the project an operational accounting framework for the assessment of external costs of energy technologies, named ExternE (Externalities of Energy) was developed. USA suspended participation in the project at the end of the first phase. The methodology developed and the results obtained are widely accepted and have been used to support other studies and projects, some relating to different sector or regions like APERC (2005), Venema and Barg (2003), Nuclear Energy Agency (2003), HEATCO (2006) among many others[45].

In the ExternE project series, the impact pathway methodology was developed, improved and applied to calculate externalities from electricity, heat production and transport. The project takes into account externalities associated with each stage of the fuel cycle in power generation and includes three broad categories of impacts: environmental, global warming and accidents. Over the years, several changes in methodology have been introduced during the project phases and proposed in follow-up projects like NewExt[46] or NEEDS[47] among many others. A full description of the methodology proposed and followed in this research project may be found in European Commission (1995a and 1998) and Bickel and Friedrich (2005). Table 4.1 shows a summary of the main impacts described in this project for fossil fuel cycle, nuclear fuel cycle, wind fuel cycle and hydro fuel cycle.

[45] A list of projects related with ExternE may be found in http://www.externe.info/.
[46] http://www.ier.uni-stuttgart.de/forschung/projektwebsites/newext/
[47] http://www.needs-project.org/

According to the general results of the ExternE study, of all the fossil fuel cycles' impacts which have been valued in monetary terms, impacts on global warming and the public health damages due to air pollution are the most relevant (European Commission, 2003).

Table 4.1- Main impacts of electricity generation technologies. Source: ExternE project

Fossil fuel cycles[(1) (2)]	Nuclear fuel cycle[(3)]	Wind fuel cycle[(4)]	Hydro fuel cycle[(4)]
Effects of atmospheric pollution on human health, on materials, on crops, on forests, on freshwaters fisheries and on unmanaged ecosystems. Impacts of global warming. Impacts of noise. Accidents affecting workers and/or the public. ***Coal and lignite fuel cycles*** Impacts of coal and lignite mining on ground and surface waters. Impacts of coal mining on building and construction. Resettlement necessary through lignite extraction. ***Oil and gas fuel cycles*** Effects of accidental oil spills on marine life. Effects of routine emissions from exploration, development and extraction from oil and gas wells.	Radiological and non-radiological health impacts due to routine and accidental releases to the environment. Occupational health impacts, from both radiological and non-radiological causes.	Accidents affecting the public and/or workers. Effects on visual amenity. Effects of noise emissions on amenity. Effects of atmospheric emissions related to the manufacture of turbines and construction and servicing of the site.	Occupational health effects. Employment benefits and local economic effects. Impacts of transmission lines on bird populations. Damages to private goods (forestry, agriculture, water supply, ferry traffic). Damages to environmental goods and cultural objects.

(1) European Commission (1995c) (2) European Commission (1995d)
(3) European Commission (1995e) (4) European Commission (1995b)

The most relevant impacts of the Portuguese coal fuel cycles are those caused by atmospheric emissions originating from the power generation stage. They contribute to global warming and can affect human health. Impacts from occupational and public accidents are also significant in the Portuguese context. As for the gas cycle in Portugal, the major impacts reported are related to global warming effects (Martins et al., 1998).

ExternE results indicate that the impacts of atmospheric emissions from wind fuel cycle are insignificant in comparison to those from fossil fuels. The most important environmental effects of operating wind turbines are impacts on human amenity, namely noise and visual intrusion. As for the hydro fuel cycle, ExternE results show that the hydroelectric development has almost no atmospheric emissions and the main impacts are on land use, cultural objects and on aquatic and terrestrial ecosystems. The major impacts are local and immediate, contrasting with fossil fuel cycles. In Portugal, the analysis of the hydro fuel cycle has shown that ecological impacts were of major importance for the evaluation of the externalities of hydro developments. Socio-economic benefits derived from the creation of a lake and from the construction of new infrastructures associated with hydro power were not assessed but, within the Portuguese context, these positive externalities could reach a significant figure (Martins et al., 1998).

Figure 4.7, drawn from European Commission (2003) report summarises the main results of the ExternE project.

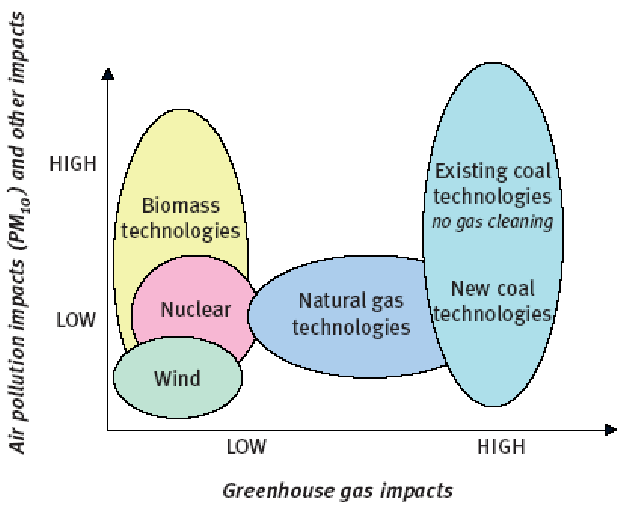

Figure 4.7- Overall results of the ExternE project. Source: Drawn from European Commission (2003)

In general, wind technologies are environmentally friendly with respect to emissions of pollutants, including greenhouse gas emissions. However, the results also indicate some variability of the external costs assigned to wind due to noise or other amenity impacts, depending mostly on the local conditions of each plant analysed. Nuclear technologies present low emissions and generate low external costs, even when considering the low probability of accidents with very high consequences. As for biomass, due to the large number of technologies the variation of external costs is high, although in general they generate very low greenhouse gas emissions in their life cycle. Gas-fired technologies are quite clean, with respect to classical pollutants (not including greenhouse gases), but depending on the efficiency of the technology, they may have an impact on climate change due to CO_2 emissions. Coal technologies generate high CO_2 emissions, even for new, more efficient technologies. Old coal-fired power plants are highly polluting units for every type of pollutants considered (European Commission, 2003).

For fossil fuels, global climate change is a fundamental issue which very much dominates current energy and environmental policy. For nuclear fuel, the potentially large consequences of an accident, and the long term impacts of radioactive waste are the main decision drivers. The expansion of renewable energy technologies has resulted in increasing opposition in parts of the affected local population because of increasing amenity impacts. Potential impacts on local ecosystem from, e.g. hydro plants, offshore wind parks or biomass plantations in particular have raised objections from green interest groups which traditionally consider renewable technologies as a viable alternative to nuclear power (Krewitt, 2002). Mirasgedis et al.'s (2000) calculations indicate that mortality, associated with the effects of air pollution and the global warming effect are the most important components of the externalities attributed to conventional power plants. For biomass fired power plants, the external costs associated with global warming are considered to be zero and the high priority impacts are close to the ones identified for the conventional oil plants. As for wind and hydropower plants, the main external cost components refer to noise and occupational accidents.

A different study developed in the USA (Roth and Ambs, 2004) reached similar conclusions. Costs associated with externalities are generally higher and more subject to uncertainty for fossil fuel technologies with high emission rates than for cleaner, more efficient technologies. For most fossil fuel power plants the major external costs were associated with GHG emissions, other pollutant emissions and with energy security depletion issues.

Although renewable energy sources are generally associated with lower external impacts comparatively to fossil fuel fired plants and in particular to coal, they are not absolutely impact free. In fact, important negative impacts have been studied for some of the most frequently used renewable energy technologies.

IV.3.1 Hydropower impacts

Concerning the hydropower sector, a large number of advantages or positive impacts can be described, namely (Almeida et al., 2004; US Department of Energy[48]; World Bank [49]):

- Energy impacts, associated with: the economic value of the electricity and power supplied, the economic benefits of the reserve potential, the dynamic response facility of these technologies and the avoided emissions. Additionally it is a domestic and renewable power source. REN (2006a) underlines that the high levels of availability and production flexibility are two major advantages of hydropower plants.

- Water resource impacts, associated with their contribution to irrigation, water supply and minimal ecological flows during dry season.

- Social-economic development impacts, associated with the creation of new activities related to sport or tourism, which generate new employment and diversify the economy. Also agriculture activity may benefit from flood control and water availability. Most hydropower installations are required to provide some public access to the reservoir to allow the public to take advantage of these opportunities.

However some important disadvantages or negative impacts are also reported in the literature (Almeida et al., 2004; US Department of Energy[12]; World Bank[13]; International Rivers Network[50]):

- Environmental impacts, associated the loss of habitats and biodiversity, loss of fish community, landscape alterations or obstruction of fish migratory movements. Dams, also change the pattern of the river’s flow, reducing its overall volume and changing its seasonal variations. All parts of a river’s ecology can be impacted by changes to its flow.

[48] http://www1.eere.energy.gov/windandhydro/hydro_ad.html (information drawn in June 2007).
[49] http://www.worldbank.org/html/fpd/em/hydro/ihd.stm (information drawn in June 2007).
[50] http://www.irn.org/index.php?id=basics/impacts.html (information drawn in June 2007).

- Energy impacts. The electricity production capacity is strongly dependent on the rainfall conditions.

- Socio-economic impacts. New hydropower may compete with other land uses that may be more highly valued than electricity generation. Local population may lose their habitat and lands. Local cultures and historical sites may be impinged upon.

- Amenity losses. Noise and vibration due to construction activities may disturb local wildlife and human populations.

A detailed description of the hydropower impacts may be found in The World Bank[44] site, along with a description of possible mitigation measures.

The World Commission on Dams (2001) supports the view that dams have been promoted as an important mean of meeting water and energy needs and as a long-term, strategic investment with the ability to deliver multiple benefits. Regional development, job creation and fostering of an industrial base with export capability are often cited as benefits. However, such benefits need to be weighed against the social and environmental impacts of large dams. The enormous investment required to build large dams, and their huge social, environmental and economic impact, make them highly contentious projects.

IV.3.2 Biomass impacts

Bioenergy is a very heterogeneous aggregation of different feeding materials, conversion technologies and end-uses. In the European context, biomass is taken to include agricultural and industrial wastes in addition to forest woodfuel, and it is regarded as a potential source of heat, fuel and electricity (McKay, 2006). The main positive and negative impacts of biomass technologies reported in the literature are listed below:

- Environmental impacts. As with other forms of combustion, wood fuel combustion emits air pollutants. The amount and type of pollutants depends both on the specific combustion process involved and on the extent of controlled burning. Compared with fossil fuels, combustion plants fired with forest residues emit similar levels of nitrogen oxides, but significantly less sulphur dioxide (Miranda and Hale, 2001).

On the other hand, forest management and the removal of residues can contribute to reducing fire risk, especially in forests that are currently unmanaged.

Carbon neutrality of biomass is not accepted by all experts. ExternE results (European Commission, 2003) indicate that biomass technologies generate very low GHG emissions in their life cycle. Many argue that carbon dioxide emissions are irrelevant because forest residue carbon is part of the natural carbon cycle, and will eventually be taken up again in new forest biomass (see for example Saéz et al., 1998 or Thornley, 2006). The growing of energy crops fixes carbon from the atmosphere by photosynthetic process, this way compensating the carbon dioxide released on combustion. However, other studies indicate that carbon uptake by growing biomass occurs much more slowly than carbon release during combustion, estimating that after 80 years 13% of the carbon released from residue combustion may remain in the atmosphere (Miranda and Hale, 2001).

Other environmental impacts of biomass include emissions from additional vehicle movements and the plant itself, environmental effects of herbicides, pesticides and fertilisers used during crop cultivation, any changes in soil fertility, mineral and carbon balance and ecological impacts on natural and semi-natural habitats and on the biodiversity supported (Thornley, 2006).

- Energy impacts. Among renewable energy sources, biomass is one of the few resources whose availability does not depend on weather conditions, seasonal or diurnal variations and can be stored, for use on demand (Thornley, 2006). This represents an important advantage, allowing electricity generation from biomass to be highly predictable and contributing to base load capacity. Additionally, it is a domestic energy source and contributes to the diversification of the fuel mix and security of supply.

- Socio-economic impacts. Bioenergy projects involving energy crops can make a significant contribution to rural income or employment increment. Energy crops lead to changes in agricultural labour patterns and give positive contributions to rural economic diversification (Thornley, 2006). Results of surveys on local public opinion of a proposed biomass gasifier in the UK indicate that potential employment impact was the most highly confirmed benefit (Upham and Shackley, 2007).

The transport and infrastructure requirements and associated emissions of new biomass capacity may also result in an adverse reaction from sections of the local community (Thornley, 2006). Upreti (2004) presents some examples demonstrating that a major barrier to promoting biomass energy is local opposition.

In general, biomass technologies have fewer environmental impacts compared to the conventional sources. Additionally, they bring important benefits to rural populations and contribute to security of electricity supply. However, there are still important local impacts that can raise concerns and generate opposition to the development of biomass power plants. The effects of pollutant emissions are a major concern along with the loss of quality of life caused by increased traffic and the plant installation.

IV.3.3 Wind power impacts

A large number of studies have been published addressing the impact of wind power development on the environment, on socio-economic development, on the operation and security of the electricity system and on the final cost of the supplied electricity.

Manwell et al. (2002) pointed out that wind energy development has both positive and negative impacts. On the positive side, the authors emphasise that wind energy is generally regarded as being environmentally friendly when compared to large scale conventional electricity generation power plants. However, as more wind turbines have been installed, the importance of their negative impacts has become more noticeable.

The most frequently reported problems for wind farms are the visual impacts and noise, with the perceived visual quality of wind turbines in the landscape being the major factor in the public’s opinion . Additional cited concerns include the impact on birds and wildlife and aspects related to the integration of wind power into electric grids associated with the perceived unreliability, high cost and low efficiency. Others less frequently reported impacts are the electromagnetic interference and land use (Devine-Wright, 2005 and Wolsink, 2007)

➢ Avian interaction with wind turbines

Wind power plant development can adversely affect birdlife due to bird electrocution and collision, change of foraging habits, reduction of available habitat and disturbance of breeding and nesting. However, positive aspects may also derive from this development, such as the protection of land from habitat loss, provision of perch sites for roosting, hunting and nesting or the protection of birds from indiscriminate harassment (Manwell et al., 2002).

There is no consensus among experts about the importance of wind power plants' impacts on birds. Travassos et al. (2005) and Fielding et al.'s (2006) literature reviews indicate that studies in this field are far from homogeneous. The results depend on issues like the location of the wind farms, the type of birds analysed or the weather conditions. ExternE's report on wind (European Commission, 1995b) assigned medium priority to this impact and concluded that existing European studies and experience do not provide evidence of significant impact to birds from turbine collisions or from disturbance. By contrast, Drewitt and Langston (2006) concluded that although many of the studies carried out are either inconclusive or indicate that effects are not significant for a given species, site and season, this should not be used as justification for poor or inadequate assessments of future developments. According to these authors, the relatively few studies that do indicate a significant impact are a clear warning that inappropriate location of wind farms can adversely affect wild bird populations.

At the Portuguese level, the Portuguese Society for Bird Study (Travassos et al., 2005) support the view that wind power plants may have negative impacts on bird life. This report describes in detail the direct impacts (bird collision with turbines) and indirect impacts (loss of habitat and change of habits) and presents a review of international literature on the subject. However, this report also indicates that technology development along with an increased concern about local problems and the adaptation of generators' working conditions contribute to the reduction of the number of accidents. In line with this, Manwell et al. (2002) present some mitigation measures to minimise these impacts, including a careful choice of location, tower design or locally adapted management measures among others. Likewise, BirdLife (2005) supports the view that adverse impacts on wildlife must be avoided by full evaluation of suitable alternatives and by appropriate location and design.

- **Visual impact of wind turbines**

Wind power plants have been the subject of hard criticism because they are a new element and because they are sometimes located in highly visible places in order to exploit wind conditions (Kaldellis et al., 2003). The landscape impacts are exacerbated by the fact that the locations with the highest wind resource are often precisely those exposed upland areas which are valued for their scenic qualities and which are often ecologically sensitive (Moran and Sherrington, 2007).

Authors like Bishop and Miller (2007), Manwell et al. (2002) and Kaldellis et al. (2003) agree that one of the majors public concerns and an important factor determining public opposition to wind farms is their visual impact. The ExternE project considered the visual intrusion of turbines and associated equipment as a high priority impact of wind projects (European Commission, 1995b).

Attitudes towards the visual impact of wind turbines are not well established and the landscape assessment is somewhat subjective (Manwell et al., 2002). Bergmann et al.'s (2006) survey on attitude towards renewable energies indicates that the aesthetic pleasure of a wind project is a contentious matter. Some people feel that wind plants are pleasing to observe and represent clean energy while others find them intrusive and a spoiler of the scenic qualities of the landscape.

Wolsink (2007), reviewed some works on public attitude towards wind power, concluding that visual evaluation of wind power impact on the landscape is by far the dominant factor in explaining why some are opposed to wind power implementation while others support it. Devine-Wright (2005) presents the view that despite the predominant emphasis of the literature on the negative visual impacts of turbines, there is little evidence that wind turbines are universally perceived as ugly.

Attitudes towards the impact of wind power on the landscape vary across different countries. The Toke et al.'s (2007) review indicates that landscape protection organisations vary in strength in a range between England/Wales (very strong and influential) to Spain (non-existent), and so the importance assigned to the aesthetic side of wind power plant varies from country to country. According to Álvarez-Farizo and Hanley (2002), conserving flora and fauna from wind farm developments is ranked more highly than either preserving the landscape or protecting the unique cliffs in Spain. On the other hand, studies in UK reveal that preservation of valued landscape motivates most of the opposition (see for example TNS, 2003 or Warren et al., 2005).

- **Wind turbine noise**

Noise levels can be measured but the public's perception of the noise impact of wind turbines is highly subjective. The ExternE project assigned high priority to this impact and supports the view that although technical adjustments can be expected to reduce the problem, the public perception of the effects of wind turbine noise can still be significant (European Commission, 1995b).

Wind farms can be built without significant detriment to noise amenity provided that the turbines are placed at sufficient distance from the houses. Appropriate sitting and planning conditions are essential to minimise this impact, but as Manweel et al. (2002) noted, due to the wide variation in individual tolerance to noise, there is no completely satisfactory way to predict unfavourable reactions.

Both mechanical and aerodynamic noise produced by wind turbines has diminished with technology improvement (Manwell et al., 2002 and Moran and Sherrington, 2007). According to Kaldellis et al. (2003) due to the present generation of quiet machines, noise is a minor problem for modern carefully sited wind turbines. However, studies like van den Berg (2004) demonstrate that this is not yet a negligible issue. This author studied the noise levels of a wind park in Germany, where residents living 500 metres and more from the park reacted strongly to the noise while residents up to 1900 m distance expressed annoyance. The main conclusions were that actual sound levels were considerably higher than predicted, and that wind turbines can produce sound with an impulsive character, increasing annoyance further.

IV.3.3.1 Integration of wind power on the power system

The inclusion of power sources of variable output distributed through a large electricity grid has important effects on the control of the grid and delivery of stable power. As the load changes during the day, generators are brought online but larger prime movers may take a while to prepare for generation (Manwell et al., 2002). Capital-intensive plants with low operational costs such as nuclear or coal power plants are high merit or base load plants and will be in operation for as many hours as possible. Intermediate or mid merit plants are usually conventional plants brought on line but operating at part load operation. Low merit present low specific capital costs and quick-start capability but frequently high variable costs such as Single Cycle Gas Turbine (SCGT). Also the hydropower or pumped storage plants can be used during peak load periods.

To ensure the balance between supply and demand, the system operator needs to have a level of operational reserve power for unexpected variations, typically in a time range of less than an hour. The introduction of large amounts of wind power into the grid increases the short term variability of the supply, increasing the need for operational reserve (Manwell et al., 2002). The variable production pattern of wind power changes the scheduling of the other production plants and the use of the transmission capacity between regions (Holttinen and Hirvonen, 2005). Because of this, integrating wind energy into complex power systems is expected to incur system costs in excess of those incurred by equivalent amounts of energy delivered to the system on firm, fixed schedules (Dragoon and Milligan, 2003).

Hoogwijk et al. (2007) specify the high load following capability of the generation mix (generation that can ramp at a relatively high rate) and the degree of interconnection with other grids, as very important factors for dealing with variable supply of wind power. The authors pointed out the benefits of combining wind power with hydro power or biomass, to smooth out the variability of wind. This work and Holttinen and Hirvonen's (2005) emphasise also the importance of forecast tools for wind power production. Accuracy of wind forecasts contributes to risk reduction and to the reduction of the required additional reserves. An accurate forecast allows the system operator to rely on wind capacity, improves the utilisation of wind sources and lowers operational costs without jeopardizing the system reliability.

In Portugal, Esteves et al. (2003) favour the usage of hydro pumping schemes to compensate for the random variations imposed by the wind component. REN (2005) predicts the installation of SCGT plants for operational reserve that will contribute to balance renewable production. Those units allow for a rapid mobilisation of the power capacity, particularly in the case of hydropower, which can be very responsive to load fluctuations and can be brought on line quickly.

In the specific case of Portugal, wind power electricity generation also presents a variable pattern. On December 7th 2006, the maximum output of the year was achieved with a peak utilisation capacity equal to 84%. On the other hand in January 8th 2006, the average load factor equalled only 2% over the day (REN, 2007b). At intradaily level, volatility of wind power production is also high. On September 21st 2006 the difference between maximum and minimum output of the day reached 900 MW. On February 8th 2007 the wind power loss achieved 468 MW in an hour (between 20h00 and 21h00), greater than the installed power of the biggest conventional thermal group (Pestana, 2007), as shown in Figure 4.8. The variations of wind power were particular remarkable in that day. In three hours (between 10h00 and 13h00) the wind power output was reduced by 500 MW and in the following four hours (between 13h00 and 17h00) the wind power output increased by 800 MW. On that day, the increase in electricity importations and the increase in hydro power production compensated for the loss of wind power in Portugal, demonstrating the flexibility and dynamic value of the hydro system.

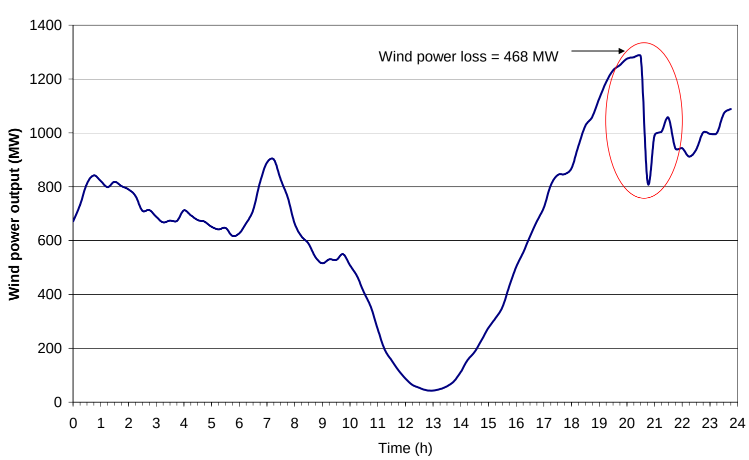

Figure 4.8- Hourly wind power output, Portugal, February 8th 2007. Source: Own elaboration of REN website (data drawn in June 2007).

- **Impact on generation cost**

Dragoon and Milligan (2003) divide costs associated with wind integration into two relatively broad categories: The incremental reserve requirements and the imbalance costs.

The incremental reserve requirements category encompasses the increased need for primary, secondary and tertiary reserve. Primary reserve corresponds to the production capacity that is activated within 30 seconds from a sudden change in frequency. According to Holttinen and Hirvonen (2005) and Dragoon and Milligan (2003), the impacts of wind power production in this primary control are very small. Wind power impacts will be felt mainly on secondary and tertiary reserve levels. Secondary reserve corresponds to the production capacity that is activated 10 to 15 minutes after the deviation in frequency occurs. This is also called the fast reserve and is ensured by rapidly starting thermal and hydro power groups, load changes in the groups in operation and load shedding. Tertiary reserve, also called long term or slow reserve involves estimation of loss of load probability and estimation of the long run peak capacity. The influence of wind on tertiary reserve requirements is directly related with the capacity credit of wind power.

The imbalance costs category captures the difference in system operating costs experienced by a system that meets the load with an incremental amount of wind resources versus the same system meeting an identical load with an incremental amount of energy equivalent to the wind project, but delivered at constant rate. Such costs may include costs of additional unit start-ups or units that are forced to operate at less favourable points on their power curves.

Also Holttinen and Hirvonen (2005) refer to the need for increased reserve requirements as a result of use of wind power, describing the extra costs due to both the allocation and the use of the reserves. In addition, the optimised unit commitment becomes more complex due to the variable wind power output. This may result in decreasing efficiency of the system with thermal power plants operating bellow the optimal level or increasing the number of start ups, with consequent negative impacts on the amount of fuel used and emissions released. Recent works like Holttinnen and Pederson (2003) for the West Denmark, ESB National Grid (2004) for Ireland or Rosen et al. (2007) for Germany, addressed the effect of wind power on thermal system operation, concluding that in general adding wind power to the system does in fact increase average thermal power production costs.

The capacity credit of wind represents the amount of conventional generation that can be displaced by wind generation, without affecting the reliability of the total system. The capacity credit of wind varies with the relative proportion of wind in the system. With low penetrations of wind, the variable nature of wind has very little impact on the need for additional plant margin. However, as the wind capacity becomes larger the distribution of wind output becomes increasingly important and reduces its capacity credit (Dale et al., 2004). The ESB National Grid (2004) report demonstrated that the capacity credit attributable to wind decreases progressively and tends toward zero. With increasing amounts of wind capacity, the total installed power rises significantly because the amount of non wind plants falls off by a relative small amount.

According to Hoogwijk et al. (2007), at low penetrations the capacity credit is about equal to the load factor. For a system with up to 5–10% of its installed capacity in the form of wind turbines, most system operators accept 20–30% of the installed wind capacity as guaranteed. The consequence of the low capacity credit of wind is that the reserve margin has to be increased by the installation of back-up capacity with good load-following capability.

Estimates regarding the increase in average electricity cost in Ireland, including fixed and variable costs, suggest a 15% increase of cost for a penetration close to 12% and 24% increase in cost for a wind penetration close to 20%, over the no wind scenario (ESB National Grid, 2004). For UK, Dale et al. (2004) estimated a 11% cost increase for a wind penetration close to 20%, in comparison to a conventional scenario in which electricity was produced mainly by thermal power generation.

Besides the additional system capacity cost and additional system balancing cost, grid reinforcement/extension requirements and corresponding costs may also be relevant. This is a fundamental aspect for Portugal, where most of the wind potential is located in inland hill regions with low consumption and underdeveloped electricity networks. There is an excess of inland production that must be transported to the big electricity consumption centres, which implies the reinforcement of the national transmission grid (REN, 2005).

Under the Green Net project, Auer et al. (2005) concluded that to date there is lack of experience and empirical data on grid related aspects in the context of large-scale RES grid integration. The authors reviewed country specific studies and presented indicative values for the grid reinforcement/extension cost caused by additional wind generation, in the range of 0.1 to 5 €/MWh of wind, depending on the wind penetration in a system.

In conclusion, the quantification of the impact of large scale wind power on the total generation cost must not be based on assumptions of straightforward substitution of electricity generation technologies. Increasing levels of wind power production affects both the level of power system reserve and the fuel consumption of conventional plants. Avoided costs to the system result primarily from reduction of fuel consumption, as wind energy will reduce the amount of fuel burnt in gas and coal power stations. However, coal and gas units operate less efficiently when part loaded, increasing the operating costs per MWh of the thermal power plants. Also, penetration of wind generation imposes the need for additional flexibility on the system operation and increases the reserve requirements of the system, resulting in additional capital costs that have to be committed to maintain system reliability.

- **Impact on emissions reduction**

The electricity production in wind power plants is free from emissions. As such, wind power contributes to offset emissions from conventional fuel fired power plants, including greenhouse gas, NO_x, SO_2 and particulates. The amount of emissions abatement depends on the types of power plants being replaced and also on the system operating efficiency.

Large wind power scenarios result frequently in the reduction of coal and gas consumption of thermal power plants. However, as described in the previous section, losses of efficiency of thermal power plants may occur for high wind power scenarios, increasing the average fuel consumption per MWh generated and consequently also increasing the overall emissions intensity (emissions per MWh).

The CO_2 abatement of wind power represents the CO_2 reduction allocated to wind power, measured as tonnes of CO_2 saved per MWh produced from wind. Holttinen and Pederson (2003) and Holttinen and Tuhkanen (2004) studied the effect of wind power on CO_2

abatement in the Nordic countries. Although the authors reached different absolute values, depending on the country or set of countries under analysis and in particular on the possibility of cross-border transmission, the results indicated a general decreasing trend of the CO_2 abatement value with increasing wind shares. This decreasing trend is also described by the ESB National Grid (2004) report for Ireland. Similarly, Rosen et al. (2007) concluded that in the German case along with system fuel efficiency, the emission reductions decrease with the growing share of wind energy.

Different results were obtained by Denny and O'Malley (2006) in work for the Irish electricity system. The authors showed that the benefits of wind generation in the reduction of both SO_2 and NO_x are minimal. However, in regard to CO_2, the results indicated that the emission reduction appeared to be in approximately 1:1 relationship with increasing wind levels. Voorspools and D'haeseleer (2006) simulated the operation of the Belgium power system for different wind scenarios. These authors also observed that the increase in emission reduction was only slightly sub-linear with the increase in installed power. If the installed wind power increases by a factor X, the emission reduction increases by a factor slightly below X.

The impact that wind generation has on the overall emissions of the electricity system, strongly depends on the structure of the conventional power generation capacities, the production of which is partly replaced. It seems obvious that systems based on highly polluting coal units are much more capable of achieving large emission reduction values than systems based on renewable, nuclear or gas technologies, when wind power is introduced.

IV.3.3.2 Public attitude towards wind power

In general renewable energies are supported by public opinion. In the particular case of wind power the general public attitude seems also to be positive. The level of support is high, and the environmental aspect of the application of this renewable source is the basis for the strong general support (Wolsink, 2007). The results of the European Commission's (2006b) survey on attitudes towards energy confirm the public acceptance, indicating that at the national level there is clear support for increasing the use of renewable energies.

Regardless of this expressed general acceptance, specific wind projects often face resistance from local populations (Ek, 2005). However, surveys of public attitudes have also frequently shown that large majorities of residents in areas with wind farms are in favour of wind power (Warren et al., 2005; GfK NOP Social Research, 2006; TNS, 2003).

Kaldellis (2005), however reported negative perception of wind power in some Greek regions, observing that the public attitude towards new wind energy applications was either divided or definitively against. The author concluded that this attitude was due to the considerable number of wind farms which were built in close proximity to one another and which were insensitive to local scenic facilities. He also commented on the conservative nature of the local people. In studies, on public attitude towards wind power in Sweden, Ek (2005) and Söderholm et al. (2007) concluded that in spite of the existence of local opposition, the public opinion was generally positive. Different surveys conducted in UK (GfK NOP Social Research, 2006; TNS, 2003)[51], mostly concluded that public support for renewables remains high, although some resistance to local wind power projects might be expected. This suggests that most people are not opposed to the idea of onshore wind farms per se, but do not want them installed in the area where they live. Resistance to onshore wind farms is predominantly driven by the negative perception of their visual impact.

The public resistance seems to derive not only from the perceived negative impacts of wind energy but also from the nature of the decision making process. Warren et al. (2005) mantain that people's viewpoints are critically influenced by the nature of the planning and development process. According to these authors, the earlier, more open and participatory the process, the greater the likelihood of public support. Also Wolsink (2007) supports the view that local involvement to represent the local values of site-specific landscapes is crucial and concludes that the need for a collaborative approach in making wind power implementation effective is now universally recognized.

Devine-Wright (2005) and Warren et al. (2005) present a review of studies addressing the public perception of wind energy. Based on this, Devine-Wright (2005) listed a number of variables identified in past research as affecting public perceptions of wind farms, associated not only with the characteristics of the project but also with political, socio

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[51] These and other surveys on general renewable energy or wind power are described in Department of Trade and Industry website: http://www.dti.gov.uk/energy/sources/renewables/planning/public-perception/page18642.html

economic and personal factors. Key issues include local perceptions of visual and economic impacts, the inclusiveness of the planning process, social influences, and the political and institutional context. Also Jobert et al. (2007) identify the following factors of success for local acceptance of wind energy in Germany and France: visual impact, ownership, information and participation.

In general, it appears that part of the local opposition to wind plants may be explained by institutional factors and lack of communication but, issues related to the landscape and impacts on human amenity are also highly valued and can be the drivers of negative public reactions.

IV.4 Concluding remarks

Energy production and use have unquestionable environmental impacts, contributing significantly to greenhouse gas and other pollutant emissions and causing adverse effects on human health, natural ecosystems and on private or community goods. The use of more efficient technologies along with the enforcement of sustainable energy policies have contributed to a general reduction of the CO_2 emissions intensity derived from energy consumption, particularly evident in Europe. However, the overall increase in energy consumption frequently offsets the environmental benefits achieved, as was described for the particular case of Portugal.

The need for clean energy called for the implementation of environmental regulations, where the environmental performance of the electricity production activities is a priority line of action. Important measures included the ratification of the Kyoto protocol and a large set of European Directives: on the promotion of electricity from renewables, on the establishment of the Emissions Trading Scheme and on the limitation of emissions from large combustion plants, among many others.

In regard to Portugal, the need for clean energy technologies and for environmentally driven energy policies is obvious. Energy consumption presents an accentuated rising pattern and CO_2 emissions closely follow it. According to the 2007 submission for the UN Framework Convention on Climate Change, in 2005 the GHG emissions were 42% higher than in 1990, a far greater value than the target set under the EU burden-sharing agreement.

Renewable energies have in general much lower emissions than conventional thermal power plants, thus making them strongly favoured by the environmental regulation for the energy sector. However, renewable energy technologies are not free of negative impacts and, although the public attitude towards them is generally positive, local people may react negatively to some specific projects. In the particular case of wind, relevant negative impacts on the ecosystem, noise complains and negative impacts on the landscape were reported.

Using technologies of variable output such as wind energy to produce electricity differs from generating electricity by conventional power plants. The fluctuations on wind power output occur in a random pattern and have to be compensated for by the production of schedulable, conventional capacities in the power system (Rosen et al., 2007). Because of this, wind power does not work as a simple fuel saver, since it cannot easily be controlled and accurately predicted (Olsina et al., 2007).

To properly assess the potential effects of wind power on the electricity system cost, on saved fuel and on avoided emissions, analysing how the existing generating system interacts with increasing amounts of wind power is crucial. Both the CO_2 abatement value and additional cost assigned to the system are highly dependent on the characteristics of the electricity system under analysis. As the EWEA (2005a) report underlines, the size and the inherent flexibility of the power system are crucial aspects determining the system's capability of accommodating a high amount of wind power.

Holttinen and Hirvonen (2005) concluded that wind power contributes to a reduction of final fuel usage and emissions but, at high penetration levels, an optimal system may require changes in the conventional capacity mix. Also Rosen et al. (2007) underline that an increasing scale of the fluctuations is a challenging phenomenon and the resulting effects cannot be ignored, neither in power system operation, nor in long-term energy expansion planning. Wind power variations will affect the scheduling of conventional power plants to an extent that depends on forecast as well as on the flexibility of the conventional power producers in the system area (EWEA, 2005a).

Although the possible impacts of wind power should not be neglected it is important to recognise that power systems without wind also have significant variability (Dragoon and Milligan, 2003). Thus EWEA (2005a) recalls that both electricity supply and demand are variable and that the variability of wind power can be predicted to a great extent. As for the potential negative impacts, associated with noise annoyance, landscape intrusion and ecosystem disturbance, their magnitude is highly site specific. Sitting of wind turbines is a key issue in determining the level of the impact. With appropriate design and site selection the adverse factors can be minimised (Manwell et al., 2002 and European Commission, 1995a).

In general, it seems that wind power can make an important contribution to the reduction of fuel consumption and to complying with environmental international commitments. However, the interconnection capacity, the existing generation capacity mix and the characteristics of the wind power system itself have a significant effect on how the variable production is assimilated into the system and on the extent of this contribution.

IV.4.1 A new framework to sustainable electricity planning

There is no single way to proceed with an energy project evaluation and the energy planning process. It clearly depends not only on the objective of the work but also on practical aspects like the available data and time, the specific characteristics of the region and the members of the team. As Georgopoulou et. al. (1998) state "energy planning should be seen as a complicated task to be performed in an ill-structured environment through a hardly prescriptive procedure". From the revision of the literature presented in Chapters 3 and 4, an approach to the sustainable central electricity planning problem is proposed, combining different techniques and involving several integrated steps, reflecting both mathematical evidence and value judgment considerations:

- The process must rely on a detailed analysis of the electricity system under study, including:

    - The characterisation of the present situation of the electricity system should be the first stage, as the process is based on an incremental approach.
    - The characterisation of the future prospects of the electricity system

(namely demand and electricity generation technologies).

- The description of the legal and technical restrictions expected for the planning period.

➢ The economic and environmental dimension of the problem does not directly involve the decision makers' participation but rather includes:

- The identification of all relevant costs and environmental impacts.
- The monetisation of the tradable environmental damages.
- The development of an optimisation procedure for detailing future plans for the electricity system, including all the criteria capable of being described by mathematical functions.

➢ Given the distinctive character of the social dimension, it cannot be addressed with the same analytical toolbox as the environmental and economic ones (Lehtonen, 2004). The information developed through the optimisation procedure is enriched with the perception of the decision makers, including:

- The identification of the relevant social impacts.
- The development of a framework for collecting information and value judgments from the different agents.
- The integration of these judgments into the decision process.

In the following chapters an application of this general procedure to the particular decision problem of long-range electricity planning in Portugal will be presented, based on: the characterisation of the Portuguese system presented in Chapter II; the review of the planning models conducted in Chapter III; and the description of the impacts of the electricity generation technologies presented in this chapter. The main objective is to design a sustainable integrated electricity planning model, flexible enough to be replicated and adapted for different market conditions and to accommodate the different points of views of decision makers, but at the same time to be able to incorporate all the relevant dimensions to ensure sustainable development of the Portuguese electricity system.

CHAPTER V

ELECTRICITY PLANNING MODEL

This chapter describes the formulation of multiobjective mathematical models for the electricity planning in Portugal. Both linear and nonlinear optimisation models are developed combining cost and environmental objectives. The analysis also incorporates results from reported expected results on the impact of large scale wind power on the power thermal system. The output of the optimisation process is the electricity generation schedule for the next ten years, detailing monthly plans for electricity production and yearly plans for generating capacity expansion.

V.1 Introduction

Electricity planning involves the determination of the type of electricity generation technologies and their utilisation ratios that will best meet the goals of society. As seen in the previous chapters, energy decisions are complex by nature and require awareness of the economic, environmental and social contexts within which the projects will take place. This chapter deals with the economic and environmental dimensions of the electricity planning problem. Both these aspects may be described in terms of a number and/or by mathematical expressions, allowing for the use of optimisation procedures and therefore simplifying the comparison of the alternatives.

The economic objective may be described and included in the models by a function representing the present value of total cost of the electricity generation plan, including the investment cost, fixed operation and maintenance (O&M), variable O&M, fuel and CO_2 emission allowances. In this study, for the environmental objective, total CO_2 emissions were selected as a proxy measure of the environmental impact of each electricity plan. Thus, the models minimise total electricity cost and total CO_2 emissions, meeting predefined demand of electricity in a region over a given planning horizon.

The models are built in an incrementally and centrally planned perspective. The present characteristics of the system under analysis are included and represent the starting point of the problem. The optimisation is conducted evaluating the alternative's cost and benefits by its effect on the entire system's operating costs and CO_2 emissions. A large number of constraints ensuring the reliability of the electricity system and its legal and technical requirements are also included.

The developed models were applied to the Portuguese electricity sector, based on REN (2005) electricity demand forecasts for the next ten years (2008-2017). The existing Portuguese electricity system was modelled taking into account the technologies currently being used, including: special regime producers (SRP), coal, natural gas, fueloil and large hydro power plants. According to the expected future characteristics of the Portuguese system, the new technologies considered for addition included wind, coal and natural gas.

Two main models were obtained: (i) a mixed integer linear model, where all the mathematical relationships are linear and all power plants are assumed to be operating at average conditions; (ii) a mixed integer non linear model, where the impact of the increasing wind power on the performance of the thermal power plants is incorporated. The second model is significantly more complex and resulted in a new exploratory model that demonstrates the need to address the impact that technologies of variable output may have not only on the operating conditions of the electricity system, but also on medium to long range planning.

This optimisation models follow a structure close to the one described by Hobbs (1995) for resource planning models, adapted to the Portuguese case:

- An economic objective: to minimise the capital costs and variable costs.
- An environmental objective: to minimise emissions, measured by total CO_2 emissions.
- A set of decision variables: loads carried by each electricity generation unit and installed power of each new power plant.
- A set of constraints: capacity limitations, legal requirements and electricity supply needs.
- A set of data: expected electricity demand for the planning period and technical and economic characteristics of the power plants in the system.

This study will result on the definition of future investment plans for the Portuguese electricity sector, identifying the optimal timing and size of new generation capacity and the electricity production schedule during the planning period.

The present Chapter is organised as follows:

Section V.2 describes the model formulation in the Portuguese context. Based on reports published by the electricity generation companies, the technologies presently operating in the Portuguese electricity system are characterised in relation to cost, CO_2 emissions and technical perspectives. Future available technologies are identified and also characterised according to data collected from international reports. This section presents also the demand forecasts for the 2008-2017 period and explains how these forecasts were included in the models.

Section V.3 presents the linear electricity planning model for Portugal, describing the mathematical relationships used in the model. Due to the complexity of the models, this section starts with the presentation of the notation used. The cost and emissions objective functions are then described, followed by the set of constraints included in the model.

Section V.4 outlines the optimisation process conducted, justifying the suitability of the GAMS language to solve these problems and the solver choice.

Section V.5 presents the results obtained from the linear optimisation model for Portugal. The results are described by a Pareto curve representing tradeoffs between cost and CO_2 objectives. The power generation expansion plans are detailed for the optimal points included in the curve. Results are discussed in light of the present electricity prices and the Kyoto protocol.

Section V.6 details the impact of wind power on the electricity planning. This phase of the work counted on REN collaboration and relied on empirical data collected from a CCGT presently operating in the Iberain market. Section V.6.1, describes the results of the simulation conducted for the Portuguese electricity system assuming different wind scenarios. The impacts of wind power on CO_2 emissions and on the operating cost of the electricity system were computed. From this simulation, mathematical relationships were obtained, describing the impact of wind power on CCGT operating conditions. These relationships were then included in a new non linear electricity planning model for Portugal detailed in Section V.6.2. Section V.6.3 presents the results obtained from the non linear optimisation model for Portugal. In order to check the robustness of the results of the non linear model, a sensitivity analysis was conducted as detailed in Section V.6.4.

Section V.7 discusses the results obtained from the optimisation processes conducted along the Chapter.

Finally, Section V.8 draws the conclusions pointing the main limitations of the work and indicating directions for future research.

V.2 Model formulation for Portugal

The REN (2005) report indicates that new investments in thermal power plants are expected to be based on coal or gas fired technologies. Along with this, an increase in hydro power plants and in the SRP, particularly wind power, is also projected. The first question to address during the model formulation concerns the future available technologies that should be considered for addition for the planning period assumed in the model.

V.2.1 Future available technologies included in the planning model

The European Commission (2006a) forecasts and trends for the energy sector, indicate that in the future there will be a change in the structure of the power generation, in favour of renewables (mainly driven by the high growth rate of wind power) and natural gas, while nuclear and solid fuels lose market shares. Up until 2020, a reduction in the oil, solid and nuclear power generation capacity is forecasted for the EU-25, while an increase in the gas fired installed power may be expected. In REN (2003) investment plan, this gas to power tendency was also obvious for Portugal. This report assumed an evolution of the large thermal power sector until 2025 based only on new gas fired plants. However, due to the need to diversify the energy sources reaching equilibrium between coal and natural gas, the new REN (2005) investment plan changed the reference scenarios. This new report, assumed an increase of both gas and coal generation capacity for Portugal until 2016. The oil power plants presently operating are expected to be dismantled in a few years and no new oil capacities are forecasted. Following this, the models will include as candidate thermal power plants both gas and coal power plants.

At present there are no Single Cycle Gas Turbine (SCGT) operating in the Portuguese electricity system. However, the REN (2005) foresees the integration of three 250 MW groups during the next 10 years, to work mainly as peak units. Those are low-merit plants with high operational costs, which should only be brought on-load during peak demand moments or to support the system in dry regime situations. The inclusion of SCGT on the electricity system is mainly justified by the quick response capacity of this technology. The planning model developed under this study is based on average monthly electricity demand values and, as so, does not capture the peak situations. As SCGT are mainly peak units, their future installed power will be included in the model as a parameter instead of a decision variable.

The combined cycle gas turbine (CCGT) and coal power plants are baseload technologies, meaning that their operational cost is low enough to work continuously for long periods. As the planning model assumes average demand values, these are the thermal power plants that will be meeting most of this demand. Two thermal power technologies were then considered for addition in the model: CCGT and super critical cycle pulverised coal (SCPC). The model assumes discrete capacity sizes assigned to each technology: 330 and 400 MW for CCGT groups and 300, 450 and 700 MW for SCPC groups.

Nuclear technology was not included in the model. Presently there are no nuclear power plants operating in Portugal and although some private companies have revealed some interest in investing in this technology, the present policy for the energy sector discards that possibility[52]. Thus, it seems improbable that nuclear technology is a feasible option for the next ten years.

The hydro power is a strategic sector of the Portuguese electricity system and not only for its reference electricity value. The REN (2002b) study of the hydro sector in Portugal, supports the view that the economic value of an hydro project should include: the dynamic or kinetic value of the hydro power plants associated with the intrinsic capacity of instantaneous response to large variations of supply or demand, the emergency value associated with the storage capacity of some hydro plants, and the environmental value associated with the avoided pollutant emissions. Additionally, the hydro power plants also have a fundamental contribution to the regularisation of river flows and water supply security for urban, industrial and agriculture usage. The decision to invest in new hydro power plants is a complex and long procedure involving many criteria not directly quantifiable by economic or emission factors. Additionally, this sector is fundamental to achieve the renewable objectives set by Directive 2001/77/EC and depends heavily on political decisions. Taking this into consideration, the future installed hydro power will be set as a parameter instead of a decision variable of the model, based on the REN (2005) forecasts for the sector.

SRP include the renewable (excluding large hydro power) and cogeneration power plants.

[52] See for example statements of the Prime Minister published in Jornal de Negócios in 8 March 2007.

This sector is also fundamental to meet the renewable objectives set under Directive 2001/77/EC. In order to reduce the complexity of the model, it was decided to set the non wind renewables and cogeneration production as parameters, based on their future expected values. The wind power is included as a continuous decision variable, with no discrete capacity sizes assigned to it.

According to the above explained, the identified candidate power plants to meet growing demand are: CCGT, SCPC and wind power (onshore and offshore).

Table 5.1 and 5.2 summarise technical and economic characteristics of the candidate power plants. This information was drawn mainly from the literature and based on information available for the existing power plants. The data presented assume average efficiency values for each technology, independent of the operating regime of the power plant

Table 5.1- Technical data of the candidate power plants.

Plant type	**Lifetime (years)**	**Efficiency (%)**	**Fuel consumption**	**CO_2 (ton/MWh)**	**Unit capacity (MW)[4]**	**Maximum (MW)[5]**
SCPC[1]	40	46	0.305 ton/MWh	0.738	300, 450, 700	
CCGT[2]	24	57	163.4 m^3N/MWh	0.353	330, 400	
Wind onshore[3]	20					6500
Wind offshore[3]	20					1000

[1] Efficiency and lifetime drawn from IEA/NEA (2005), for a SCPC plant with flue gas cleaning.
[2] Efficiency and lifetime drawn from IEA/NEA (2005), for a CCGT in Portugal.
[3] Lifetime drawn from IEA/NEA (2005), for a wind power plant in Portugal.
[4]Antunes et al. (2004) example.
[5]Estimated maximum feasible installed power. Values drawn from Esteves (et al., 2003), Estanqueiro (2006) and from interviews with the experts.

Table 5.2- Economic data of the candidate power plants (2005 base year)

Plant type	**Capital (€/kW)**	**Fixed O&M (€/MW)**	**Variable O&M (€/MWh)**	**Fuel**	**Fuel (€/MWh)**
SCPC[1]	1137	33.8	2.6	56.7 €/ton	17.3
CCGT[2]	517	11.3	2.2	241 €/$10^3 m^3$N	39.4
Wind onshore[3]	1213	26.6			
Wind offshore[4]	1741	61.3			

[1] Capital cost drawn from IEA/NEA (2005), for a SCPC plant. O&M cost drawn from DGEMP-DIDEME (2003) report. Fuel cost drawn from EDP (2006b).
[2] Capital cost drawn from IEA/NEA (2005), for a CCGT plant in Portugal. O&M cost drawn from DGEMP-DIDEME (2003) report. Fuel cost drawn from EDP (2006b).
[3] Capital and O&M costs drawn from IEA/NEA (2005), for a wind power plant in Portugal.
[4] Capital and O&M costs drawn from IEA/NEA (2005).

Annex 2 summarises the computation of the average fuel consumption, average fuel cost and average CO_2 emissions.

V.2.2 Planning period of the model

Hobbs (1995) indicates that the resource planning for electricity generation is usually made for a 10-40 years horizon. At this moment, it would be possible to obtain information on electricity demand forecasts up to 2030 for Portugal, from the European Commission (2006a) publication. However, public information on the future of non wind SRP, on large hydro power plants and on the dismantling of the existing power plants is not available for such a long period.

The planning period depends heavily on the data available and on the assumptions that the authors are prepared do make. Sirikum and Techanitisawad (2006) for example, tested their model simulating different planning periods (from 5 to 30 years). Antunes et al. (2004) used a 30 year planning period divided in sixth month intervals. The authors tried to use data as much as possible in agreement with the Portuguese case, although not corresponding to a real case study. Cormio et al. (2003) study covered, a 20 year planning period, considering possible scenarios for annual rates of electricity consumption. Smith and Villegas (1996) solved a capacity expansion planning for the Columbian interconnected generation system for a 10 year period.

For this particular study, it was decided to sacrifice the planning period in benefit of the accuracy of the data. Thus, the planning period will be 10 years (between 2008 and 2017)[53] which allows the use of data directly drawn from the REN (2005) forecasts. Also, it contributes to the practical computation of the model, as the planning period will be divided in months increasing highly the number of variables.

V.2.3 Characteristics of the existing and committed power plants

For the designing of the model it became necessary to describe the characteristics of the present and future Portuguese power system. This included information on plants capacities, operation costs, efficiency, emission levels and expected future dismantling.

Table 5.3 describes the installed power of each technology presently available in the

[53] The model assumes that it would be possible to initiate activity of new power plants in the beginning of the planning period, not taking into consideration the licence and construction time. Thereby, the results of the models for at least the first two years should be seen as of a theoretical study.

Portuguese electricity system, as well as new power plants assumed to be already committed[54]. Annex 1 details the present and future electricity system under REN (2005) scenarios.

Table 5.3 - Installed power of the existing and new power plants assumed to be already committed.

Plant type	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017[(2)]
Coal	1820	1820	1820	1820	1820	1820	1820	1820	1820	1820	1820	1820
CCGT	2166	2166	2166	2166	2166	2166	2166	2166	2166	2166	2166	2166
Oil[(1)]	1910	1910	1712	1712	1656	946	946	0	0	0	0	0
Large hydro	4582	4582	4582	4582	4582	4582	4951	5413	5597	5805	5805	5805
SCGT			250	250	250	500	500	500	500	750	750	750
NWSRP[(3)]	1626	2006	2199	2355	2523	2669	2784	2904	3029	3159	3245	3245
Wind	1515	1515	1515	1515	1515	1515	1515	1515	1515	1515	1515	1515

Source: REN (2006a), REN (2006b), DGGE(2007), EDP(2007), Turbogas (2006), Pegop (2006) and REN website.
(1) Fueloil, gasoil and one natural gas group in Carregado.
(2) Assumed to be equal to 2016 (based on non official documents and interviews).
(3) NWSRP- Non wind special regime produders.

Table 5.4 presents the characteristics of the existing and new power plants, including their variable costs (O&M, fuel), CO_2 emission levels and thermal efficiency. Annex 2 summarises the computation of the average fuel consumption, fuel cost and average CO_2 emissions.

Table 5.4- Data of the existing and new power plants assumed to be committed already

Plant type	O&M cost (€/MWh)	Efficiency (%)	Fuel cost	Fuel consumption	Fuel cost (€/MWh)	CO_2 (ton/MWh)
Coal[1]	2.85	40	56.7 €/t	0.349 ton/MWh	19.9	0.844
CCGT[2]	2.42	54	241 €/$10^3$$m^3$N	174 m^3N/MWh	42.0	0.375
Fueloil[3]	2.42	40	202.6 €/t	0.223 ton/MWh	45.2	0.715
Large hydro	Assuming variable costs equal to zero.					
SCGT[4]	2.25	35	241 €/$10^3$$m^3$N	266 m^3N/MWh	64.1	0.575
Wind	Assuming variable costs equal to zero.					

1 Efficiency and CO_2 emissions calculated from EDP (2006a) data. Fuel cost drawn from EDP (2006b).
2 Efficiency and CO_2 emissions calculated from Turbogas (2005) data. Fuel cost drawn from EDP (2006b).
3 Efficiency and CO_2 emissions calculated from EDP (2006a) data. Fuel cost drawn from EDP (2006b).
4 Efficiency and CO_2 emissions drawn from DGEMP-DIDEME (2003) report. Fuel cost drawn from EDP (2006b).

Due to the lack of information on O&M costs for the existing power plants, it was assumed that these costs were 10% higher than the ones reported for the candidate power plants.

V.2.4 Electricity demand forecast

The future capacity requirements of an electricity system derive directly from the expected future demand. Electricity demand forecasts are therefore a key aspect of the planning

54 By power plants already committed we refer to the future power plants included in the model as parameters as detailed in Section V.2.1: SCGT, hydro power and non wind SRP.

process. REN's (2005) forecasts indicate that between 2006 and 2016 the electricity demand in Portugal will continue to rise at an average annual rate of about 4.5%. However, the specific characteristics of the Portuguese system imply that part of the supplied electricity is not included in the dispatching process based on optimisation procedures. Taking this into consideration, part of the electricity production is assumed to be non-modelled during the planning period.

V.2.4.1 Non modelled electricity production

The Portuguese electricity system includes a few generators that have priority access to the grid (priority of dispatch) and are not included in any optimisation process for the dispatch. The legal protection granted to SRP ensures that the grid will buy all their electricity production at previously established feed-in tariffs. Additionally, about half of the Portuguese hydro system is run of river technology, with very low storage capacity, implying that the electricity production of these plants will almost exclusively depend on the river flow. Part of the hydro storage capacity is also committed to non electricity use. Therefore at particular moments, regardless of electricity 's market value, these plants will be operating to ensure water supply for urban, industrial and agriculture use. The non wind special regime producers (NWSRP), the run of river hydro generation and the share of hydro storage committed to non electricity uses are assumed to be non-modelled and should not be included in the optimisation model.

The computation of the electricity generation from the non wind SRP (NWSRP) was based on the expected installed power during the planning period (drawn from REN (2005)) and on the average load factor of each technology, obtained from historical data available in the REN website (www.ren.pt). The wind power production will be included in the model as a variable and a constraint must be imposed making sure that the total production is equal to the available capacity at each moment, reflecting the legal protection conferred to these producers.

The production from the run of river power plants was also estimated, taking into consideration the present and future installed power and the load factor of these plants. For the computation of their load factor the average monthly values verified in the 2001-2006 period were used[55]. In dry periods, hydro storage power plants work close to their minimal levels. In these periods, the electricity generated derives mainly from the need to run the power plant in order to meet the non electricity commitments. To estimate the minimum electricity production of the hydro storage plants, data on present and future installed power and the load factor of these plants in a very dry year (2005) were used. Only the difference between these minimal values and the average ones will be included as a variable in the optimisation model.

The run of river and minimum storage hydro production represent respectively about 60% and 15% of the total hydro production in an average year. Thus, only about 25% of the hydro production is assumed to be modelled.

The fuel oil plants presently installed in Tunes, Carregado, Barreiro and Setubal will be decommissioned during the planning period (REN, 2005). Tunes is presently used only in peak demand situations, and during 2006 it worked less than 6 full load equivalent hours. The production of the Carregado and Barreiro power plants is also much reduced, representing in 2006, less than 1% of the total electricity consumption. For simplification purposes, Tunes will not be included in the analysis and the production from the Carregado and Barreiro power plants will be included in the non-modelled sources. The expected production from these power plants will be calculated for each sub-period using the average load factors of previous years and included in the non-modelled production[50]. Thus, only Setubal's (with an installed power equal to 945 MW) electricity production will be included in the model as a decision variable.

V.2.4.1 Modelled electricity demand

The modelled demand/production reports the difference between the total electricity consumption and the non modelled electricity production. Figure 5.1 presents the computation of the modelled demand to be included in the planning process. The numbers represent an example of the calculations for January 2010. The process was repeated for each month of the 2008-2017 planning period.

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[55] Monthly load factors computed from information drawn from REN website (www.ren.pt).

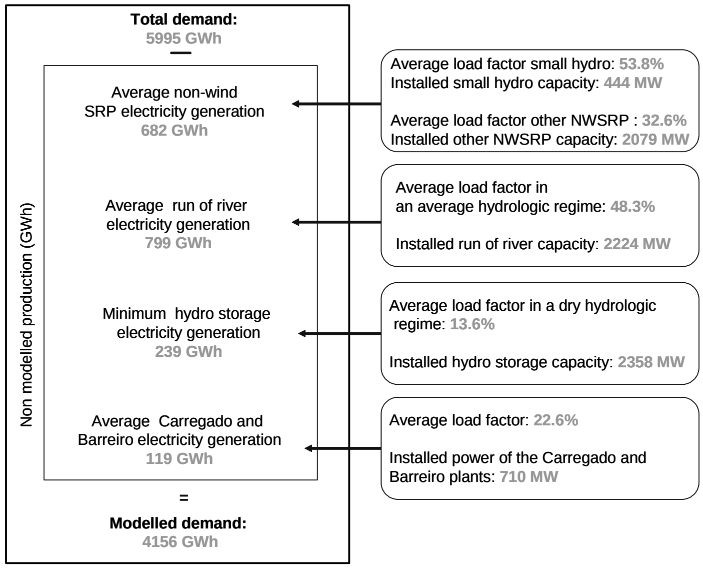

Figure 5.1- Computation of the modelled demand (example for January 2010).

The full description of the values used for the analysis of the Portuguese system may be found in Annexes 3 and 4. Annex 3 details the average load factors of the SRP, hydro and fuel oil power plants. Annex 4 presents the monthly and annual values of the total electricity demand, the non-modelled electricity production and the modelled electricity demand. This modelled demand, used in the optimisation models, represents about 75% of the total forecasted electricity demand in Portugal for the planning period considered.

V.3 Electricity Planning Model

In this section, following an introduction to the notation used in the model, a detailed description of the two objective functions and of the constraints is given.

V.3.1 Notation

V.3.1.1 Indices

k	candidate power plants				
k=1	coal	k=2	CCGT		
k=3a	wind onshore	k=3b	wind offshore		
l	existing or already commited power plants				
l=4	coal	l=5	CCGT	l=6	Fueloil
l=7	Large hydro	l=8	SCGT	l=9	wind

t planning period in years (1, 2, …, 10 years)

h time intervals in an year t (1, 2, …, 12 months)

m_k modular capacity of k type power plants

V.3.1.2 Parameters

$COEF_k$	CO_2 specific emission factor of k type power plants (ton/MWh).
$COEF_l$	CO_2 specific emission factor of l type power plants (ton/MWh).
CP_{m_k}	Modular capacity of each of the k plants (MW).
	$m_k=1_1$ 300 MW $m_k=2_1$ 450 MW $m_k=3_1$ 700 MW
	$m_k=1_2$ 330 MW $m_k=2_2$ 400 MW
D^*_{ht}	Modelled demand in interval h in year t (MWh).
D_{ht}	Demand in interval h in year t (MWh).
EC	Emission cost (€/ton).
F_k	Fuel cost of k type power plants (€/MWh).
F_l	Fuel cost of l type power plants (€/MWh).
FOM_k	Fixed O&M costs of k type power plants (€/MW-year).
HI_{ht}	Hydro inflows at period h of year t (MWh).
i	annual discount rate
I_k	Investment cost of k type power plants (€/MW)
IP_{lt}	Installed power of l type power plants in year t (MW).
$IP_{NWSRP,t}$	Installed power of non-wind special regime producers (NWSRP), in year t (MW).
$IP_{OTHER,t}$	Installed power of non-modelled fuel oil plants, in year t (MW).
LBHG	Installed power of the biggest hydro group (MW).
LBTG	Installed power of the biggest thermal group (MW).
$NMHP_{ht}$	Non-modelled hydro production in interval h of year t (MWh).
PL_t	Peak load in year t (MW).
$P^*_{NWSRPht}$	Power output from NWSRP excluding fuel and gas cogeneration, in interval h (MW).
n_k	lifetime of k type power plants.
RM_t	Reference margin in year t.
VOM_k	Variable O&M costs of k type power plants (€/MWh).
VOM_l	Variable O&M costs of l type power plants (€/MWh).

φ_{kh}	Availability factor of k type power plants, in interval h.
φ_{lh}	Availability factor of l type power plants, in interval h.
Δ_h	Length of the interval h (number of days in a month×24 h).
χ_W	Non usable wind capacity (%).
χ_H	Non usable large hydro capacity under a dry regime (%).
χ_{NWSRP}	Non usable NWSRP capacity (%).

V.3.1.3 Decision variables

The decision variables are the numerical quantities for which values are to be chosen in the optimisation problem (Coello et al., 2002).

$\theta_{m_k t}$	Total number of m_k modules of candidate power plants in year t (integer variable).
$IP_{k=3a,t}$	Total installed power of the candidate onshore wind power plants in year t (MW).
$IP_{k=3b,t}$	Total installed power of the candidate offshore wind power plants in year t (MW).
P_{kht}	Power output from plant type k in interval h of year t (MW).
P_{lht}	Power output from plant type l in interval h of year t (MW).

The variables obtained directly from the decision variables are:

R_{ht}	Reserve of the storage hydro power plants at the end of interval h of year t, computed from the $P_{l=7,h,t}$ (MWh).
IP_{kt}	Total installed power of the k type power plants in year t, computed from $\theta_{m_k t}$ (MW).

V.3.1.4 Objective functions

The objectives represent the criteria used to evaluate the quality of a certain solution. The objective functions describe mathematically the relationship between the decision variables. In the proposed Electricity Planning Model (EPM), the two objective functions are measured in different units and the aim is to find the optimum between economic and environmental aspects.

C	Total present value of cost (€).
CO	Total CO_2 emissions (ton).

V.3.2 Cost objective function

The cost objective function consists of the total present value of cost (C), which includes:

- The fixed cost (FC), corresponding to the present worth of the investment cost (I_k) and fixed operation and maintenance costs (FOM_k) of the candidate plants.
- The variable cost (VC), corresponding to the present worth of the variable O&M, fuel and emission costs of the existing, future and candidate plants,

$$C = FC + VC \qquad (€) \qquad (5.1)$$

The cost values of the plants may be found in Tables 5.2 and 5.4; the analysed year is divided in H intervals of duration, each one characterized by the demand power.

The capital investment cost is obtained for all the candidate power plants as a sum of the annuities over the planning period. The calculations are based on the uniform distribution of the investment cost during the plant lifetime and assume that this cost is incurred in the first year of the plant operation. The decommissioning cost was set equal to the final salvage value of the installations resulting in a null value.

The formula for the annualised cost (AC) of the present value of the investment cost (I_k) over the period of plant lifetime (n_k) at a given discount rate (i) is given by:

$$AC = I_k \frac{i(1+i)^{n_k}}{(1+i)^{n_k} - 1} \qquad (5.2)$$

The total FOM_k costs are also obtained for all the candidate power plants as a sum of the annual values over the planning period. As both the investment and FOM_k costs are set as a function of the total installed power of each plant type, the cost values must be multiplied by the total installed power of each power plant in each year.

For the existing power plants, the model assumes that the fixed O&M costs will always be incurred regardless of the power plant being or not used in the entire planning period. Although the plant may not be required to operate during the planning period it is assumed that these plants will still be available as reserve. As such the fixed O&M costs for the existing power plants are not included in the optimisation process.

The fixed cost may be described then as:

$$FC = \sum_{t}\sum_{k}\left\{\left[I_k \frac{i(1+i)^{n_k}}{(1+i)^{n_k}-1} + FOM_k\right] IP_{kt} \times (1+i)^{-t}\right\} \qquad (€) \qquad (5.3)$$

Due to the short planning period considered (10 years) no construction times were taken into consideration. Also, there are no restrictions on the number of available groups in the market to supply in each year. In the future, if forecasts for the electricity system for a longer period become available, it will be possible to change the present models introducing these new data and additional constraints that will take into consideration the plant construction time and the availability limitations of the market.

The total variable costs are obtained as the sum of the variable costs of each power plant (candidate and existing) during the planning period. The variable costs depend on the amount of electricity produced. As so, these specific cost values must be multiplied by the electricity produced by each power plant in each month. This production is obtained by the multiplication of the power output (P_{kht} and P_{lht}, measured in MW) by the length of the interval measured in hours (Δ_h=number of days in month h × 24h). The variable cost includes the variable O&M costs, the fuel consumption (coal, natural gas and fuel oil) and the economic value of the CO_2 emissions. This last element is based on the specific emission factor[56] of each technology ($COEF_k$ or $COEF_l$) and on the market value of the CO_2 allowances (EC), obtained from information drawn from the websites of the organized markets (EEX, EXAA and NordPool).

[56] Specific CO_2 emission factor is the amount of CO_2 released per unit of electricity produced (ton /MWh)

$$VC = \sum_t \sum_h \sum_k \left[\left(VOM_k + F_k + EC \times COEF_k \right) \times P_{kht} \times \Delta_h \times \left(1 + i \right)^{-t} \right] + \sum_t \sum_h \sum_l \left[\left(VOM_l + F_l + EC \times COEF_l \right) \times P_{lht} \times \Delta_h \times \left(1 + i \right)^{-t} \right] \quad (€) \qquad (5.4)$$

Combining equations 5.1, 5.3 and 5.4 the total cost function may be described as follows:

$$\begin{aligned} C = & \sum_t \sum_k \left\{ \left[I_k \frac{i(1+i)^{nk}}{(1+i)^{nk} - 1} + FOM_k \right] IP_{kt} \times \left(1 + i \right)^{-t} \right\} \\ & + \sum_t \sum_h \sum_k \left[\left(VOM_k + F_k + EC \times COEF_k \right) \times P_{kht} \times \left(1 + i \right)^{-t} \times \Delta_h \right] \quad (€) \qquad (5.5) \\ & + \sum_t \sum_h \sum_l \left[\left(VOM_l + F_l + EC \times COEF_l \right) \times P_{lht} \times \left(1 + i \right)^{-t} \times \Delta_h \right] \end{aligned}$$

The total cost value depends on the specific costs previously defined for each technology but also on the interest rate set by the decision maker. This function assumes constant prices, no increase rate of the O&M and no increase rate of fuel costs during the planning period. The final value obtained from equation 5.5, corresponds to the present worth of the expected costs for the next 10 years.

Costs for grid extensions are not accounted for in these cost calculations. The question of the grid costs is particularly important for the Portuguese electricity system, due to the prevalence of wind resources in inland hills with underdeveloped grid structures. However, as the model makes no assumptions on the location of candidate plants and due to the lack of information concerning grid extension costs, this cost element was not included in the analysis.

V.3.3 Emissions objective function

For the emissions objective function, CO_2 values are used as a rough proxy of the pollutant emissions. Directive 2001/80/EC focus already on the limitations of emissions of SO_2, particulate and NO_x from large combustion power plants, which is leading to the adoption of measures for their reduction (both Sines and Pego coal power plants have already presented proposals for desulphurisation projects). It seemed more relevant for the moment to focus on the CO_2 values due to the existence of clear objectives for Portugal, set by the Kyoto protocol. This protocol recognises CO_2 as the most important greenhouse gas (GHG). It should be however highlighted that future developments of the model may accommodate other pollutant emissions as additional objectives.

For the computation of the total CO_2 emissions, a specific emission factor for each technology was assumed for the existing and candidate power plants ($COEF_k$ or $COEF_l$). The total emissions are obtained as the sum of the emissions of each power plant during the planning period. These emissions are a linear function of the electricity produced by each power plant in each month.

$$CO = \sum_t \sum_h \sum_k \left[\left(COEF_k \times P_{kht} \right) \times \Delta_h \right] + \sum_t \sum_h \sum_l \left[\left(COEF_l \times P_{lht} \right) \times \Delta_h \right] \qquad \text{(ton)} \quad (5.6)$$

The first term of equation 5.6 represents the sum of the monthly emissions, released by the candidate power plants during the planning period. The second term accounts for the sum of the monthly emissions, released by the existing and commited power plants during the planning period. The final value obtained from this equation, corresponds to total CO_2 emissions expected to be released during the next 10 years.

V.3.4 Constraints

The constraints of the problem describe mathematically the restrictions imposed by the particular legal characteristics of the system, by the expected demand and load, by the technical characteristics of the power plants involved and by the security of supply assurance. These restrictions must be satisfied in order to accept the solution or solutions found as feasible. The EPM model includes inequality and equality constraints. The constraints described in the next sections define then the feasible region of the problem.

V.3.4.1 Demand constraints

In each interval of the planning period, the electricity production must be larger than or equal to the demand. The number of these constraints is 120. The excess of production, if existing, may be used for exportations or for electricity storage using reversible hydro schemes for example. The value of this excess production is assumed to be zero.

$$\sum_k P_{kht} + \sum_l P_{lht} \geq \frac{D^*_{ht}}{\Delta_h} \qquad \forall_{h,t} \qquad \text{(MW)} \qquad (5.7)$$

The left side of the equation represents the total power output from all the existing and candidate power plants in a given month (h) of a given year (t) of the planning period. The right side of the equation represents the total modelled power demanded for the same interval. This modelled power demanded is obtained by the division of the electricity demand in that given interval (D^*, measured in MWh), by the length of the interval (measured in hours). The monthly D^* values may be found in Annex 4.

V.3.4.2 Power capacity constraints

In each interval of the planning period, the production of each power plant may not exceed its production capacity multiplied by its availability factor. The number of these constraints is 720.

$$P_{kht} \leq \varphi_{kh} IP_{kt} \qquad \forall_{k \neq 3a \text{ and } 3b,\, h,t} \qquad \text{(MW)} \qquad (5.8)$$

$$P_{lht} \leq \varphi_{lh} \times IP_{lt} \qquad \forall_{l \neq 9 \text{ and } 7,\, h,t} \qquad \text{(MW)} \qquad (5.9)$$

For k=3a and 3b and l=9 (wind power) see equations 5.15-5.17. For l=7 (hydro power) see equations 5.20-5.24.

The left term of equations 5.8 and 5.9 represent the power output of a candidate or existing power plant (k or l) in a given month (h) of a given year (t) of the planning period. The right side of the equation represents the available power for that power plant in that particular interval, depending on the installed power and on the availability factor (φ_{kh} and φ_{lh}) of the generating unit.

The availability factor is computed as the ratio between the average available power in each month and the installed power for each generating unit. For the thermal power plants it was assumed that φ would be kept constant during the entire year and would be independent from the number of installed plants in the system. It was assumed an availability factor of 95% for each thermal power plant type, based on past records (EDP, 2004b). The wind and hydro power constraints will be treated independently, as described in Sections 3.4.5 and 3.4.7.

V.3.4.3 Reserve constraints

Following a classification based on the Union for the Co-ordination of Transmission of Electricity (UCTE) proposal, Figure 5.2 presents the power balance for an electricity system.

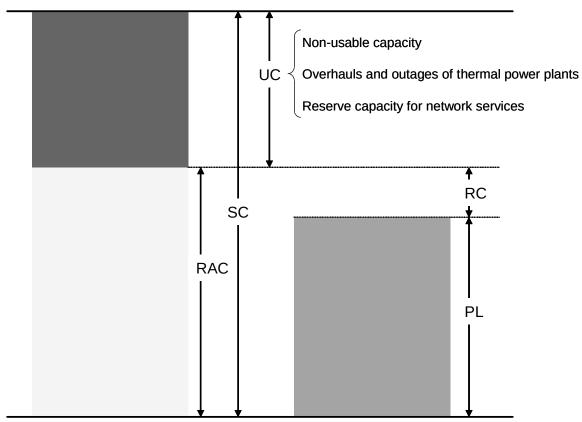

Figure 5.2- Power balance for an electricity system.

The Reliable Available Capacity (RAC) is the available generation taking into account the Unavailable Capacity (UC) computed as the non usable capacity, overhauls, outages and system reserve. The Peak Load (PL) is the maximum power absorbed by all the installations connected to the distributions or transmission systems during a year (UCTE, 2005 a and b). The System Capacity (SC) is the maximum power that the National electricity system can produce. The Remaining Capacity (RC) is defined as the capacity that the system needs to cover the exceptional demand variation and longer term unplanned outages of power plants. It represents the reserve available for power plant operators. As far as reserve is concerned, the Net Transfer Capacity (NTC) from cross-border exchanges is not included, thus assuming that each system must ensure the security of supply, regardless of the cross-border exchange possibility[57].

The RC is calculated from the difference between RAC and PL. The Reference Margin (RM_t) represents the ratio between RC and SC in each year. This RM_t is expressed as follows:

[57] The UCTE power balance does not take into account the cross-border exchanges, however it refers that "this contracts can represent a significant and permanent contribution to satisfying the national load in some countries" (UCTE, 2005a).

$$RM_t = \frac{RAC_t - PL_t}{SC_t} = \frac{SC_t - UC_t - PL_t}{SC_t} \quad \forall_t \qquad (5.10)$$

For the Portuguese case under analysis, the system capacity in each year may be described as follows from equation 5.11.

$$SC_t = \sum_k IP_{kt} + \sum_l IP_{lt} + IP_{NWSRPt} + IP_{OTHERt} \quad \forall_t \qquad (MW) \qquad (5.11)$$

In each year, the capacity of the Portuguese electricity system is then computed from the sum of the installed power of candidate and existing power plants (IP_{kt} and IP_{lt}), non wind special regime producers (IP_{NWSRPt}) and non modelled fueloil power plants (IP_{OTHERt})

The UC comprises (UCTE, 2005a):

- the non-usable capacity, which is the capacity that cannot be scheduled due to reasons like the temporary shortage of primary energy sources (hydroelectric plants, wind plants), power plants with multiple functions, in which the generating capacity is reduced in favour of other functions (cogeneration, irrigation, etc.), reserve power plants which are only scheduled under exceptional circumstances, unavailability due to cooling-water restrictions;
- the capacity of plants taken out for scheduled overhauls and maintenance and;
- the reserve capacity for network services.

According to the UCTE (2007a), in Portugal 73% of the wind power capacity at peak load cannot be considered usable and the hydropower limitations for the public system and small independent producers must also be considered. For the Portuguese case, UCTE (2005a) assumes for example that in July the power from small independent hydro producers is totally non usable and for renewable. For the cogeneration power a reduction of 50% of the generating capacity is also assumed.

In extremely dry years, the reduction of hydro production may reach values close to 60%

lower than in average years[58]. However, under these conditions the storage hydropower production will be used mainly for covering peak load, thus reducing the average hydro power production but ensuring minimal reserve levels to face extreme situations. It should be also taken into account that the expected reinforcement of the hydro sector in Portugal will be accomplished also with reversible hydro schemes, which increases the security of the system. Although the non-availability of the hydro production depends on the season and on the development of the hydro capacity, the model assumes that in extreme situations of dry years and at peak load, 30 % of hydro capacity is non-usable.

The DGE (1999) report presents power balances for Portugal until 2010. In this report, the computation of the UC assumes an extreme situation: loss of capacity due to a dry regime and the loss of the biggest thermal and hydro groups. The Available Capacity is calculated as the difference between the SC and the UC. This report focused only on the public electricity system, in particular in the large hydro and thermal power production. In 2003 and 2005, new reports were released taking now into consideration the increasing importance of SRP in the Portuguese system. However, for the moment these reports remain confidential.

Both REN and UCTE principles for reserve calculations imply the calculation of UC, based on shortage of renewable energy sources (RES) and on the loss of power capacity. Based on their proposals, the present model assumes the simultaneous occurrence of the following situations for the UC calculation:

- Lack of wind: 73% of the wind power capacity non-available.
- Dry regime: 30% of the hydropower capacity non-available.
- Reduction of 50% of the generating capacity of NWSRP.
- Loss of the biggest thermal power group.
- Loss of the biggest hydropower group.

For the computation of the unavailable capacity in each year, equation 5.12 was adopted.

$$UC = \chi_W \left(IP_{9t} + IP_{3at} + IP_{3bt}\right) + \chi_H IP_{7t} + \chi_{NWSRP} IP_{NWSRPt} + LBTG + LBHG \quad \forall t \quad (MW) \quad (5.12)$$

[58] In 2005 the hydraulic productivity index (HPI) was 0.41, meaning that the hydropower production during this period was 59% lower than and the hydropower production that would be expected under average hydro conditions.

The right side of the equation represents the sum of:

- the reduction of wind power due the lack of wind (χ_W)
- the reduction of hydro power due to a dry regime (χ_H),
- the loss of part of the NWSRP power (χ_{NWSRP}) and,
- the loss of the biggest thermal and hydro power groups . (LBTG and LBHG)

The system must also have a level of operational reserve power for unexpected variations in supply or demand, typically in a time range of less than one hour. For the identification of the proper means for energy production the time necessary for the mobilisation of the reserve power and the load variation gradients must be considered (Esteves, et al., 2003). REN studies (Esteves et al., 2003) indicate that, if the installed wind power in Portugal reaches 4150 MW, wind power variations in a time range of one hour can be above 1100 MW. REN recommends the use of hydro pumping schemes to ensure the rapid mobilization of the operational power reserve, allowing also for hydro pumping in periods of higher source affluence and simultaneously contributing to the accomplishment of the renewable objectives. Additionally, the last REN investment plan (REN, 2005) already forecasts the installation of three single cycle gas turbine groups to work as peak units.

Figure 5.3 shows the Portuguese power balance in 2016, according to REN (2005) projections.

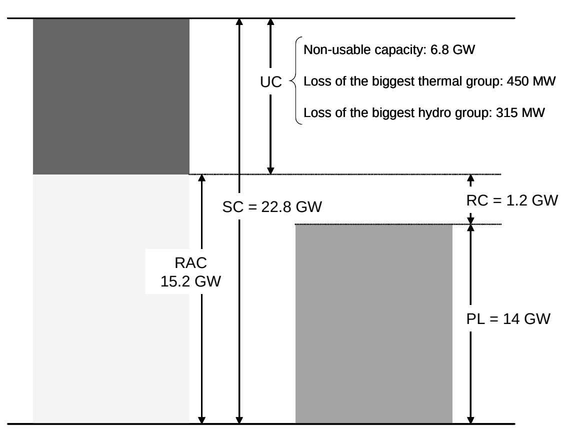

Figure 5.3- Expected power balance for the Portuguese electricity system in 2016. Source: Own elaboration of REN (2005) data.

Combining Figure 5.3 information with equation 5.10 the value of the RM for the REN

(2005) scenario in 2016 (reference scenario) may be computed:

$$RM_t = \frac{15.2 - 14}{22.8} = 0.05 \qquad \text{for t=2016, under REN scenario}$$

For the model formulation, it will be assumed that in each year the value of the RM must be at least equal to the value obtained under the reference scenario. Combining equations 5.10, 5.11 and 5.12 the expression for the reserve constraint may be obtained:

$$0.05 \leq \frac{\sum_k IP_{kt} + \sum_l IP_{lt} + IP_{NWSRPt} + IP_{OTHERt} - \left[\chi_w \left(IP_{9t} + IP_{3a,t} + IP_{3b,t}\right) + \chi_H IP_{7t} + \chi_{NWSRP} IP_{NWSRPt} + LBTG + LBHG\right] - PL_t}{\sum_k IP_{kt} + \sum_l IP_l + IP_{NWSRPt} + IP_{OTHERt}} \qquad \forall_t \tag{5.13}$$

The number of these constraints in the model is equal to 10. As mentioned, the minimum value of RM_t is parameter of the model, set according to the reference scenario obtained from REN (2005) forecasts for 2016.

V.3.4.4 Renewable constraints

Directive 2001/77/EC states that after 2010, 39% of the Portuguese electricity consumption must come from RES. Given the large share of hydroelectricity production in Portugal, the rainfall is the climate factor with the strongest impact on electricity production from RES. Using an approach followed in the Portuguese reports in the frame of this Directive, hydro production will be corrected by the hydraulic productivity index (HPI) (equal to 1.22) of the base year of the Directive (1997). The Renewable constraint is expressed as follows:

$$\frac{\sum_h \left[\left(P_{3a,ht} + P_{3b,ht} + P_{9ht} + \overset{HPI_{1997}}{1.22}\ P_{7ht} + P^*_{NWSRPht}\right) \times \Delta_h + \overset{HPI_{1997}}{1.22}\ NMHP_{ht}\right]}{\sum_h D_{ht}} \geq 0.39 \qquad \forall_{t \geq 3} \tag{5.14}$$

The numerator of equation 5.14 represents the total production from RES in a given year t, including:

- electricity production from candidate wind power plants (obtained from $P_{3a,ht}$, $P_{3b,ht)}$ and electricity production from existing wind power plants (P_{9ht}),
- modelled electricity production from hydro storage power plants (obtained from P_7) and non modelled electricity production from hydro power plants (NMHP) and,
- electricity production from NWSRP excluding fuel and gas cogeneration (obtained from P^*_{NWSRP} and presented in Annex 5).

The denominator of the equation represents the total electricity demand in the same given year (t). This ratio must be at least equal to 39% for every year after 2010, which is the same as saying for t≥3. The number of these constraints is equal to 8.

This renewable constraint sets the minimum share of the electricity produced from RES equal to 39%. This limit represents a parameter of the model that may change due to legal, political or technical reasons in the next years. For example, as mentioned before the European Commission (Commission of the European Communities, 2007) proposed already new targets to increase the level of renewable energy in the EU's overall mix to 20% in 2020, which will require the drawing of new objectives for each Member State's electricity sector.

V.3.4.5 Wind constraints

According to the present regulations of the Portuguese electricity sector, renewable energy production has priority dispatch and the electricity produced from RES is always accepted to the grid. The mathematical formulation of this legal protection to wind power is presented by equality constraints described by equations 5.15- 5.17:

$$P_{3a,\,ht} = \varphi_{3a,\,h} \times IP_{3a,\,t} \qquad \forall_{t,\,h} \qquad (MW) \qquad (5.15)$$

$$P_{3b,\,ht} = \varphi_{3b,\,h} \times IP_{3b,\,t} \qquad \forall_{t,\,h} \qquad (MW) \qquad (5.16)$$

$$P_{9ht} = \varphi_{9h} \times IP_{9t} \qquad \forall_{t,\,h} \qquad (MW) \qquad (5.17)$$

The wind power output in each interval (h) of each year (t) is set equal to the available capacity. This available capacity depends on the installed wind power ($IP_{3a,t}$, $IP_{3b,t}$ and IP_{9t}) in each year and on the availability factor of wind in each month (φ_{3a}, φ_{3b} and φ_{9}). These monthly values reflect the wind seasonality and were computed as the average of the values recorded during the last six years (2001-2006)[59]. Due to the inexistence of information in regard to the availability factor of offshore and future onshore wind power plants, φ_{3a} and φ_{3b} were set equal to φ_{9} in the model. Annex 3 presents these values. The number of these equality constraints is equal to 360.

V.3.4.6 Plant capacity constraints

For the thermal power plants, a limited set of modular capacities in the market were assumed. Thereby, for each year the total installed power of the candidate PCSC and CCGT plants must be equal to an integer value multiplied by the available modular capacities of the candidate plants. The number of these constraints is equal to 20.

$$IP_{kt} = \sum_{m_k} \theta_{m_k t} \times CP_{m_k} \qquad \forall_{t,\, k \neq 3a \text{ and } 3b} \quad \text{(MW)} \qquad (5.18)$$

The capacities for each technology were previously defined and included as parameters in the model (CP_{m_k}, in MW). $\theta_{m_k t}$, is a variable describing the number of units with capacity equal to CP_{m_k} installed between the beginning of the planning period and year t. No impositions were made in regard to the number of modules available in the market in each year.

As IP_{kt} represents the total installed power of k type power plants available in the system in year t, a new constraint must be added to the system ensuring that the value of IP_{kt} is increasing during the planning period.

$$IP_{kt} \geq IP_{kt-1} \qquad \forall_{t \geq 2,\, k \neq 3a \text{ and } 3b} \qquad (5.19)$$

The number of these constraints is equal to 18.

[59] Values computed from information drawn from REN website (www.ren.pt).

V.3.4.7 Hydro constraints

The hydro constraints are based on the initial reserves on the hydro storage hydro plants and the expected inflows. The hydro storage reserve at the end of a given month (R_{ht}, measured in MWh) must be equal to the reserve at the beginning of the month ($R_{h1,t}$) plus the hydro inflows to the plant in that given month (HI_{ht},measured in MWh), subtracted by the plant production in that period (computed by the power output $P_{7h,t}$ and by the number of hours in the month Δ_h). The mathematical formulation of the constraint involves two different equations: one for January, depending on the reserve values of December of the previous year (equation 5.20) and another one for the other eleven months, depending on the reserve values of the previous month in the same year (equation 5.21).

$$R_{h=1,t} = R_{h=12,t-1} + HI_{h=1,t} - P_{7,h=1,t} \times \Delta_{h=1} \qquad \forall_{t,\, h=1} \quad \text{(MWh)} \qquad (5.20)$$

$$R_{ht} = R_{h-1,t} + HI_{ht} - P_{7,ht} \times \Delta_{h} \qquad \forall_{t,\, h\neq 1} \quad \text{(MWh)} \qquad (5.21)$$

The initial reserve is assumed to be equal to the value in the beginning of 2006. The monthly inflows were computed based on the average values between 2001 and 2006 and on the expected increase of the installed capacity of the hydro power sector[60]. These monthly inflows may be found in Annex 6. It was also assumed that the final value of the reserve (December 2017) should be equal to the initial one. These initial value was set as a parameter in the model.

$$R_{12,10} = \text{Initial reserve} \qquad \text{(MWh)} \qquad (5.22)$$

The number of these constraints is equal to 120. A minimum and maximum reserve levels were also assumed, avoiding the model to unrealistically accommodate water or to completely deplete all the water reserves. For this two additional constraints were included for each month of each year:

[60] Values computed from information drawn from REN website (www.ren.pt). It should be highlighted that most of the 2001-2006 years present HPI below the average and are strongly influenced by an extremely wet year (2005), which may lead to some underestimation of the expected hydroelectricity production.

$R_{ht} \geq 1200000 \qquad \forall_{t,h} \qquad (MWh) \qquad (5.23)$

$R_{ht} \leq 3000000 \qquad \forall_{t,h} \qquad (MWh) \qquad (5.24)$

This value was estimated from the minimum levels presented in 2005 and from the maximum levels computed from REN monthly statistics information[61].

V.3.4.8 Natural gas constraint

The operating characteristics of the Portuguese electricity system described in Section II.4 of this thesis, indicate that coal power plants output should be relatively stable and CCGT although being mainly operated as baseload units are able to provide a little more flexibility to the system. It seems then unrealistic to think that during a month the power production could come only from coal power plants, SRP and hydro power plants as this would necessarily imply significant variations on coal power output and/or a very favourable hydro regime.

Ideally the model should include a constraint ensuring a minimum operating regime for each coal power plant. However, the present model does not deal with individual power plants and data are aggregated in monthly values, which create difficulties on the definition of operating constraints. To tackle this problem and with the aim of preventing unrealistic solutions, a proxy constraint was used ensuring that at least a minimal amount of electricity would come from CCGT operation every month. During 2006, the electricity production from CCGT reached the minimum level in November equivalent to an average power output of 310 MW[62]. It was then decided to set the minimal electricity production from CCGT equal to the average power output of that month:

$P_{2,ht} + P_{5,ht} \geq 310 \qquad \forall_{h,t} \qquad (MW) \qquad (5.25)$

[61] Source: www.ren.pt

[62] Source: Monthly information drawn from REN site.

V.3.4.9 Bound constraints

All the production values must be positive, $\theta_{m_k t}$ is also a positive and integer variable.

$$P_{kht} \geq 0$$

$$P_{khl} \geq 0 \qquad \forall_{k,l,h,t} \qquad (5.26)$$

$$\theta_{m_k t} \geq 0 \quad \text{Integer variable}$$

The total installed wind power should not overcome the assumed wind potential, based on the environmental and economic viability of these power plants. Esteves et al.'s (2003) study indicates an onshore wind potential of about 7700 MW, assuming more than 2500 full load hours. In 1993, Van Wijk and Coelingh (EWEA, 2005b) assessed the technical onshore wind resource for OECD countries and indicated the value of 15 TWh/year for Portugal. Assuming 2500 full load hours availability, this value corresponds to about 6000 MW of installed capacity. However, due to the development of the wind technology this value may now be too conservative.

For this study an onshore wind potential for Portugal of about 8000 MW was assumed. Taking into account that by the end of 2006 about 1500 MW were already installed, the limit to the total installed power for onshore wind power plans ($IP_{3a,t}$) was set equal to 6500 MW.

To the authors knowledge there are not many studies focusing on offshore wind potential in Portugal. The Commission funded CA-OWEE project (Concerted action on offshore wind energy in Europe) (EWEA, 2005b) estimates 2-3 TWh/year as the offshore wind potential for Portugal. Assuming 2500 full load hours, this value corresponds to installed wind power of 800 to 1200 MW. Estanqueiro (2006) indicated that the offshore potential should be higher than 1000 MW in Portugal. For the present study a conservative estimate of 1000 MW was assumed as the offshore wind potential in Portugal. Accordingly the total installed power for offshore wind power plans (IP_{3bt}) must not be greater than 1000 MW.

$$0 \le IP_{3at} \le 6500 \qquad \forall_t \qquad (MW) \qquad (5.27)$$

$$0 \le IP_{3bt} \le 1000$$

V.3.5 Final considerations

Figure 5.4 shows the flow diagram for the EPM, including the input information, output results and the optimisation problem.

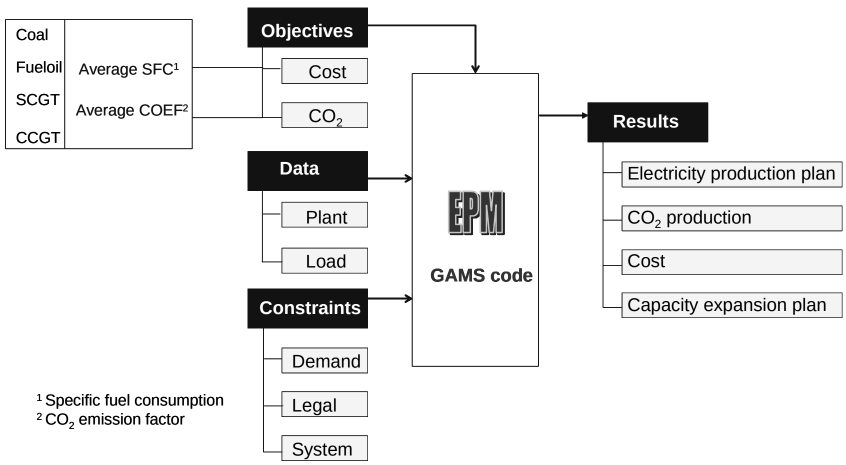

Figure 5.4- Electricity planning model.

The input information for the problem includes the mathematical formulation of the objectives and constraints. These constraints may be classified as:

- Demand, ensuring that the demand for electricity is always met over the planning horizon.
- Legal, representing the legal and political impositions to the system (renewable and wind constraints).
- System, which take into account the technical characteristics of the system and of the power plants (capacity, reserve, hydro and natural gas).

The input data describes the technical and economic characteristics of the existing and candidate power plants and the expected load (demand) pattern. This linear model assumes average specific fuel consumption[63] and CO_2 emission factors for each type of thermal power plant. Annexes 1 to 6 present the data used in the model, including installed power of the existing power plants, average and peak load, NWSRP, average hydro inflows and the computation of the estimated modelled demand. The proposed model includes the following data modules:

- Information on all the generating units in the system at the start of the study and a list of retirements and fixed additions to the system.
- Information on the various generating units to be considered as candidates for expanding the generating system.
- Information on demand, peak load for the planning period and the previously committed production (non-modelled).

The model does not deal with individual power plants but with technologies. Average values for the efficiency, CO_2 emission factors and specific fuel consumption are considered for each technology based on the average operating conditions occurred in previous years (for existing power plants) and on the expected performance of future power plants. It should be also underlined that the model does not foresee compensation payments for plants that although not producing or producing very little during the planning period would still be available as reserve. The model assumes that the fixed O&M will always be incurred even for these non-operational power plants.

The proposed EPM was written in a GAMS (General Algebraic Modelling System) code compiling all the data and calling an optimising solver according to the model characteristics. Table 5.5 summarises other general assumptions considered under the base scenario of the EPM.

The problem resulted in a multivariable constrained mixed integer linear programming (MILP) model that involves several variables both continuous and integer and is linear in the objective functions and the constraints.

[63] Specific fuel consumption is the amount of fuel consumed per unit of electricity produced (m^3N/MWh for CCGT and ton/MWh for coal and fueloil).

Table 5.5- General assumptions of the EPM

Planning period	2008-2017	
Costs	expressed in € of 2005 base year	Portuguese GDP deflator. Source: Eurostat.
Real discount rate	5%.*	
CO_2 emission costs	22 €/ton*	Average value at the beginning of 2006. Source: EEX, EXAA and NordPool.
Coal cost	56.7 €/ton*	Source: EDP (2006b)
Natural gas cost	241 €/$10^3$$m^3$N*	Source: EDP (2006b)
Fueloil cost	202.6 €/ton	
Demand sub-periods	Monthly	
Reference Margin	5%	REN scenarios for 2016 (see Section V.3.4.3)
Initial reserve	1437 GWh	Source: REN site (January 2006)

* Changes considered under sensitivity analysis.

V.4 The optimisation process

Problems in engineering, economics, physics and social sciences often involve several objectives. If these objectives are opposing, it is necessary to find the best possible solution that satisfies the opposing objectives subject to certain restrictions. A multiobjective optimisation problem may have a possible uncountable set of solutions, which when evaluated produce vectors whose components represent trade-offs in objective space. The aim of this kind of problems is to find good compromise solutions. The set of variables that produces the optimal outcome is designated as the optimal set and is referred to as the *Pareto optimal*.

The *Pareto optimal* of a problem may be defined as (Coello et al., 2002):

"(..) $\vec{x}^*$ is a Pareto optimal if there exists no feasible vector $\vec{x}$ which would decrease some criterion without causing a simultaneous increase in at least some other criterion (..)"

The region of points formed by the Pareto optimal solutions is called the Pareto front. The decision maker's task in a multiobjective problem is to select compromise solutions drawn from the Pareto front. This selection depends on the acceptable objective performances, according to the decision maker's point of view. Figure 5.5 represents the Pareto front for an example of a problem with two objectives (f1 and f2).

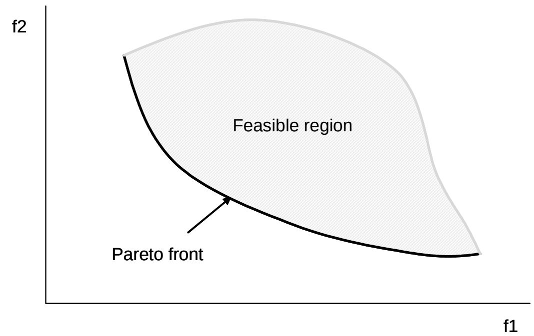

Figure 5.5- Pareto front for a problem with two objective functions.

The objective of the research is now to find the Pareto front for the bi-objective EPM. Optimisation manuals like Coello et al. (2002) or Collette and Siarry (2003), present a description of the available multiobjective optimisation techniques currently in use. For this particular model, the ε constraint method or trade-off method will be used. This method consists in the minimisation of one objective at a time, considering the other as constraints bounded by allowable levels (ε).The Pareto front can be found by varying these levels.

Following Coello et al.'s (2002) notation, for a problem with a vector $\vec{x}$ of n decision variables and a vector $\vec{f}(\vec{x})$ of k objective functions:

$$\vec{x} = \begin{bmatrix} x_1 \\ x_2 \\ .. \\ x_n \end{bmatrix} \quad \text{and} \quad \vec{f}(\vec{x}) = \begin{bmatrix} f_1(\vec{x}) \\ f_2(\vec{x}) \\ .. \\ f_k(\vec{x}) \end{bmatrix}$$

the trade off method may be represented as:

$$\min \vec{f}_r(\vec{x})$$

subject to:

$$\vec{f}_l(\vec{x}) \leq \varepsilon_l \qquad \text{for} 1=1,2,...,k \ \text{ and } l \neq r$$

This method was chosen for three main reasons:

- the problem involves only two objectives, generating a limited set of combinations that will result in a set of solutions that can reasonably describe the Pareto front.

- The method is especially suited for this particular case because the allowable levels for CO_2 may be drawn directly from the Kyoto objectives for Portugal.

- no particular assumption has to be made on the cost objective, since the Pareto front will derive from the minimisation of the cost objective and varying the CO_2 allowable levels.

With this approach the multiobjective model will be treated as a constrained single objective problem. The cost function will be the primary objective and the CO_2 function will be treated as a constraint. Varying the CO_2 allowable levels will make possible obtaining a set of solutions representing trade-offs between cost and environment.

A preliminary analysis was performed to identify the proper boundaries for the minimum allowable levels which also allowed the analysis of the degree of conflict of the two objectives. For this, independent single-objective optimisations were carried out for each objective function.

To solve the EPM, the model was described in a GAMS code. This language is specially suited to solve large linear, nonlinear and mixed integer optimisation problems. It makes possible to call for different solvers according to the specific characteristics of the problem. A more detailed description of this programming language and some examples of GAMS models may be found in the web page (www.gams.com) and in the users' guides Rosenthal (2006) and McCarl (2006).

For this particular model the Branch and Bound (BB) algorithm was used. This is one of the most common approaches to solve mixed integer linear and non linear problems (Winston, 1994 and Murray and Shanbhag, 2007) and it is also recommended by GAMS solvers to solve large problems. The BB method uses a partitioning method for the decision variables to divide all the feasible solutions into subsets and serially searches for the optimum solutions for the most promising subsets. It includes a group of procedures that attempts to perform the enumeration intelligently, so that not all combinations of variables need to be examined.

The optimisation process starts with obtaining the relaxed solution of the problem. If this solution satisfies all the integer requirements the process is finished and the solution is returned as the optimal integer. If an integer solution is not realised, the feasible region for the discrete variables is subdivided (branching) and bound on these discrete variables are tightened to new integer values to cut off the current non-integer solutions.

The searching procedure is terminated by a tolerance criterion previously defined by the user, computed in GAMS as the relative gap between the found solution and the estimated best solution (usually obtained by the solver from the relaxed problem). For example if the user sets this tolerance equal to 0.05, the process will stop when a solution is found within 5% of the best guess global optimum.

A detailed description of the BB method may be found in Edgar and Himmelblau (1989), in the Baron solver manual (Sahinidis, 2000) or in Jensen and Bard (2003).

According to GAMS web information, BARON (Branch and Reduced Optimisation Navigator) solver is suitable for searching for the global optimal of a mixed integer linear or non linear problem. BARON is a computational system for solving optimisation problems to global optimality. Purely continuous, purely integer, and mixed-integer nonlinear problems can be solved with the software. It implements deterministic global optimisation algorithms of the branch and bound enhanced type that are guaranteed to provide global optimal, under the availability of finite lower and upper bounds on the variables. Neumaier et al. (2005) tested several complete global optimisation solvers and concluded that among the currently available global solvers, BARON is the fastest and most robust[64]. However, Murray and Shanbhag (2007) reported some problems using this solver due to the high computational time required. In spite of the expected long time required to solve large problems using BARON, it was decided to use this solver at least for this linear model.

According to the above stated, the approach to the EPM involved the following main stages:

(1) Minimisation of the CO_2 objective, using the BARON solver.

[64] The study did not include integer constraints in the test set.

(2) Minimisation of the cost objective, using the BARON solver.

(3) Definition of the CO_2 allowable levels between (1) and the CO_2 value obtained with the minimisation of the cost objective (2).

(4) Minimisation of the cost objective constrained by the CO_2 allowable levels, using BARON solver

(5) Construction of the final set of optimal solutions.

The GAMS code for the EPM solver may be found in Annex 7.

V.5 Results of the EPM

Firstly, independent single-objective optimisations were carried out for both cost and CO_2 objective functions, thus obtaining the extreme solutions. Each one of these solutions corresponds to a different generating system combining different technologies and production strategies: one for the least costly solution and another for the lower emissions solution. The aim was to obtain the extreme solutions, described by the cost and CO_2 values and the capacity expansion plans. These first results are shown in table 5.6. The elements in the main diagonals (in grey) represent the ideal values and the other elements indicate the corresponding value for the other objective. The results are presented both in absolute values, corresponding to the total cost and emissions for the ten years planning period, and unit values, corresponding to the cost and CO_2 emission values per MWh produced.

As mentioned before, for the problem optimisation we used BARON global solver and the relative optimality tolerance (Optcr) was set equal to 0%.

Table 5.6- Results of the single objective optimisation.

	Absolute values		**Unit values**	
	Cost (M€)	**CO_2 (Mton)**	**Cost (€/MWh)**	**CO_2 (ton/MWh)**
Optimal cost solution (S0)	16683	314.46	31.655	0.597
Optimal CO_2 solution (S9)	20592	103.99	39.073	0.197

The elements in the first row indicate that the least cost solution (31.6 €/MWh) corresponds to an average value for CO_2 emissions of 0.597 ton/MWh. The elements in the second row indicate that the least pollutant solution (0.197 ton/MWh) corresponds to an average cost of about 39.1 €/MWh[65]. This means that the least cost solution is 19% less expensive than the solution with lowest emissions. However, it may be observed that corresponding emission levels are more than 3 times higher than the ones obtained with the least CO_2 solution.

The process proceeded with the bi-objective optimisation, with each of the objectives limited by the extremes previously identified. The Pareto solutions were found from the minimisation of the cost objective and by varying the CO_2 values between the optimal CO_2 solution and the value corresponding to the optimal cost solution.
As the CO_2 objective is described by the total emissions expected to be released in the 10 year planning period, the equivalent constraint imposes also limits to this total value (the Kyoto protocol establishes an average limit for the 2008-2012 period). Tightening of the maximum allowable emission levels may be expected in the future. Instead of using average CO_2 levels for the period, if needed, the model may be easily adapted to account for a maximum annual level.

Table 5.7 presents the results of the optimisation process. The elements in the second column represent the absolute optimal cost solution constrained by the CO_2 level indicated in the third column. The fourth and fifth columns represent the respective unit cost and CO_2 values. The last column presents the run time for each simulation.

Table 5.7- Results of the two objective optimisation.

Cost	Absolute values		Unit values		Run time
optimisation	Cost (M€)	CO_2 (Mton)	Cost (€/MWh)	CO_2 (ton/MWh)	(min))
S0	16683	314	31.655	0.597	159.4
S1	16905	275	32.077	0.522	39.4
S2	17075	250	32.400	0.474	18.2
S3	17259	225	32.748	0.427	115.0
S4	17531	200	33.265	0.379	114.0
S5	17837	175	33.845	0.332	177.3
S6	18254	150	34.636	0.285	25.3
S7	18814	125	35.699	0.237	6.5
S8	19414	110	36.838	0.209	14.1
S9	20592	104	39.073	0.197	0.1

All the models were formulated using GAMS and solved on a Pentium IV, 3.2 GHz computer with 512MB memory. When setting the relatively optimally tolerance equal to 0% and depending on the runs, Baron solver took between less than a minute and close to 3

[65] It should be underlined that these cost values represent average costs of the system, not comparable with marginal cost supported by the consumers and reported under daily markets.

hours to find the optimal solutions.

Figure 5.6 represents graphically the set of compromise solutions, corresponding to the average cost vs. CO_2 trade-off. The two extreme points of the obtained curve correspond to the extreme solutions presented in Table 5.6.

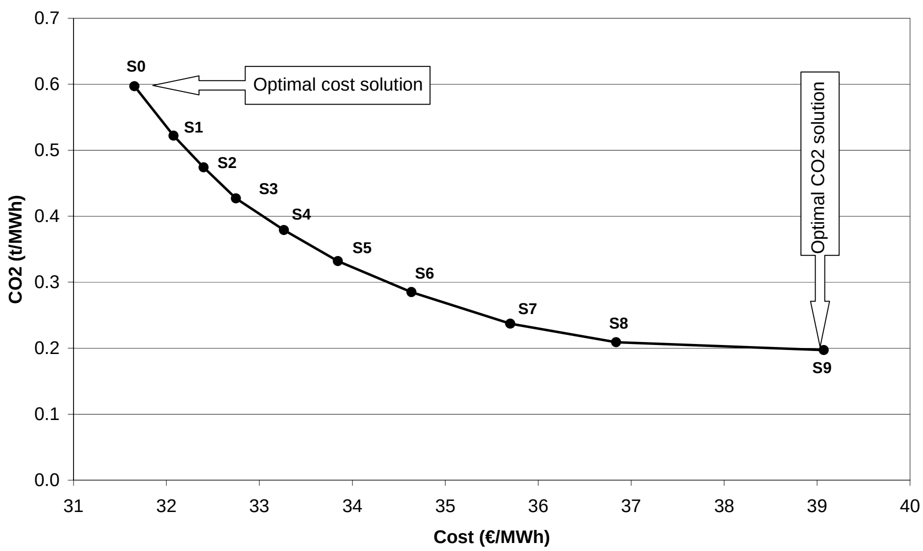

Figure 5.6- Pareto curve solutions for the EPM

Table 5.8 describes the power generation expansion planning for these solutions. Table 5.9 presents the corresponding final configuration of the electricity system in 2017, described by the total installed power for each technology and by the respective contribution for electricity supply.

From the results it can be observed that the least cost solution points to investments mainly in new coal power plants. New wind power appears only after 2010 due to Directive 2001/77/EC, imposing a minimum share of electricity produced from RES equal to 39% in Portugal. According to this solution, in 2017:

- The electricity supply would come mainly from new and old coal power plants.
- Old and new CCGT would also be operating but representing only about 4% of the electricity supply.

- The remaining electricity would come from non thermal power stations namely, wind power (about 15%), large hydro (about 14%) and NWSRP (about 11%). The share of electricity generated by these power plants is significantly affected by their low availability ratios. For example, the total installed wind power represents about 23% of the total installed power but its contribution for electricity supply is only 15%. Likewise, the large hydro power capacity represents about 24% of the total installed power but its contribution for electricity supply is only 14%.
- The electricity consumption from the renewable energy sources would represent 39% of the total electricity demand (meeting but not exceeding the renewable Directive 2001/77/EC).

- About 64% of the electricity consumption would come from imported primary energy sources (mainly coal).

Table 5.8- Annual incremental installed power (MW) for the optimal solutions.

		2008	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**Total**
	Coal	2250				600		700		600	300	4450
S0	Gas							330				330
	Wind			1481	292			106	263	368	1666	4176
	Coal	1850						750		600	700	3900
S1	Gas							330				330
	Wind	10	532	992	727	963	1184	1041	826	154	28	6457
	Coal	1150					300	1000	300	450	700	3900
S2	Gas							330				330
	Wind	10	1531	769	685	2170	1102				190	6457
	Coal				900	300	300	900	300	600	600	3900
S3	Gas							330				330
	Wind	5700	775									6475
	Coal				450	300	300	300				1350
S4	Gas				400			1130		660	730	2920
	Wind	6500										6500
	Coal											
S5	Gas				990	330		1390	400	400	730	4240
	Wind	6500								15		6515
	Coal											
S6	Gas				990	330		1390	400	400	730	4240
	Wind	6500								15		6515
	Coal											
S7	Gas			730	660	330	330	660	660	330	660	4360
	Wind	6500										6500
	Coal											
S8	Gas	1130	330	330	330	400		330	400	400	660	4310
	Wind	6500				282	718					7500
	Coal											
S9	Gas	3930		330	800	400			800	800		7060
	Wind	7500										7500

Table 5.9- Configuration of the electricity system in 2017 to the optimal solutions.

		S0	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**
Total installed power (MW)	Coal (new)	4450	3900	3900	3900	1350					
	Coal (existing)	1820	1820	1820	1820	1820	1820	1820	1820	1820	1820
	Gas (new)	330	330	330	330	2920	4240	4240	4360	4310	7060
	Gas (existing)	2916*	2916*	2916*	2916*	2916*	2916*	2916*	2916*	2916*	2916*
	Wind (new)	4176	6457	6457	6475	6500	6515	6515	6500	7500	7500
	Wind (existing)	1515	1515	1515	1515	1515	1515	1515	1515[a]	1515	1515
	Large hydro	5805	5805	5805	5805	5805	5805	5805	5805	5805	5805
	NWSRP[(1)]	3245	3245	3245	3245	3245	3245	3245	3245	3245	3245
	Total	24257	25988	25988	26006	26071	26056	26056	24646	27111	29861
Contribution for electricity supply (%)	Coal (new)	43	38	38	38	13	0	0	0	0	0
	Coal (existing)	13	11	11	11	11	10	0	0	0	0
	Gas (new)	3	3	3	3	28	41	41	42	41	51
	Gas (existing)	1	2	2	2	1	2	12	11	10	0
	Wind	15	21	21	21	22	22	22	21	24	24
	Large hydro	14	14	14	14	14	14	14	14	14	14
	NWSRP	11	11	11	11	11	11	11	11	11	11
	Total	100	100	100	100	100	100	100	100	100	100
Share of RES (%)[(2)]		39	46	46	46	45	46	46	46	48	48
External dependency (%)[(3)]		64	58	58	58	58	58	58	57	55	55
2017 electricity demand						85951 GWh					

*Includes 750 MW SCGT.

[(1)] NWSRP- Non wind special regime producers. Includes the production from cogeneration and renewable sources except wind and large hydro.

[(2)] Share of electricity consumption from RES. Large and small hydro power share corrected by the HPI (equal to 1.22) of the base year of Directive 2001/77/EC (1997).

[(3)] Proportion of energy used in meeting the demand for electricity that comes from imports.

The least CO_2 emissions solution represents a completely different scenario. It assumes a complete disinvestment on coal, and high investments in cleaner energy sources, maximizing the use of wind. According to this solution, in 2017:

- The electricity supply would derive mainly from new gas power plants.
- Old coal power plants would not operate and no new coal plants would be added to the system.
- The remaining electricity would derive from non large thermal power stations namely, wind power (about 24%), large hydro (about 14%) and NWSRP (about 11%).
- Electricity consumption from renewable energy sources would represent 49% of the total electricity demand (outreaching the renewable Directive).
- About 55% of the consumed electricity would derive from imported primary energy sources (coal and natural gas).

The initial effect of imposing increasing CO_2 constraints on the model is a reduction of investment on new coal power plants combined with the increasing investment in onshore wind power. Large investments in new natural gas power plants only appear for moderate and high environmental restrictions, which happen from solutions S4 onwards. New wind power installations no longer exist only to compile with renewable Directive 2001/77/EC. Even scenarios with low environmental restrictions assume investment in new wind power plants right from the first year.

For solutions S1 and S2, reduction of the CO_2 levels comparatively to the optimal cost solution, is achieved by the replacement of the coal power production by wind power production. Nevertheless, strong investments are committed to coal power plants in the first year and wind power shows an increasing trend all over the planning period. Solution S3 presents a configuration similar to S2 in 2017, but the investment scheduling shows a different pattern: strong initial investments in wind power technology and only after 2010, new coal power plants are included. Only for higher environmental constraints (solutions S4 onwards) will CCGT production significantly compete with coal power electricity generation.

The curve presented in figure 5.6 indicates that the drop of CO_2 emissions is not linearly related with cost increase. The slope of the curve is much higher for the points on the left than for the points close to the right extreme, meaning that the first CO_2 gains are less expensive to achieve. Computing the ratio $\frac{\Delta CO_2}{\Delta cost}$ between the optimal cost solution and S6 the value obtained is 9.55 €/tonCO_2. Computing the same ratio between solution S6 and the optimal CO_2 solution, the value obtained is 50.42 €/tonCO_2.

Between the optimal cost solution and S6, the reductions on CO_2 levels are mainly achieved through the replacement of investments in new coal power plants by investment in less polluting units, in particular wind. This substitution brings considerable environmental gains. Solutions S6 and onwards propose no coal power production in the system. CO_2 reductions may only be achieved by the installation of new CCGT that will replace less efficient existing CCGT. Although important CO_2 reductions may also be achieved, those are much costlier than the ones obtained for the initial range of the curve.

According to these results, in 2017:

- For solutions S1 to S4, new coal power plants would still be added to the system, but their share of electricity supply would be declining.

- Old coal power plants would be operating until solution S5.

- Despite the reduction on coal share, coal power plants would still account for 49% of the total electricity supply for solutions S1-S3, for about 24% for solution S4 and for about 10% for solution S5.

- For solutions S6 and onwards, the electricity supply would derive mainly from natural gas power plants and production from new CCGT would be increased.

- Solution S4 presents some degree of equilibrium between coal and natural gas. The values of the total installed power and electricity supplied by both technologies would reach close values.

V.5.1 Discussion of the results

The results of the EPM for Portugal indicate that an important degree of conflict exists between the cost and environmental objectives, with the increasing CO_2 abatement requirements calling for increasing financial effort for the assumed demand and operating conditions of the model. As the reduction of CO_2 is not linearly related with the cost increase, this financial effort is particularly significant for strong environmental restrictions. The least costly solution is the one with higher coal level, leading also to higher CO_2 emissions. When environmental constraints are imposed, the least expensive way to comply with these restrictions is the replacement of coal by new wind power plants. New CCGT are included in the system only when the assumed onshore wind potential is achieved. If strong environmental restrictions are imposed (S6-S8), even the production of existing CCGT power plants is replaced by new CCGT, but the CO_2 reduction gains per unit of cost are much lower than the values obtained for the initial solutions of the model (S1-S6).

Although wind power generation may displace part of the energy produced by large thermal power plants, it has a limited capacity to displace conventional installed power. For example, between the optimal cost solution and S1 there is an increase of about 2281 MW of the wind power capacity, however the capacity of the thermal power plants reduces only by 550 MW. As wind power is a technology of variable output its contribution to the security of supply in peak moments is considered to be low and, according to the imposed reserve margin constraint, 73% of the wind power is assumed to be non-available. Thereby, this constraint limits the amount of conventional installed capacity displaced by wind power, reflecting the low capacity credit assigned to wind.

Onshore wind power has a fundamental role on the achievement of the Kyoto protocol commitments. Coal still has an economic advantage but, due to the rising of natural gas prices, the CCGT electricity production costs are becoming close to the wind power production costs. This rising trend of natural gas prices is creating a competitive advantage to wind power. In spite of the planning model penalties imposed to wind power, where the reserve margin constraint assigns additional reserve costs to wind plants, the imposition of CO_2 limitations leads to a direct increase of onshore wind power and only on a later stage to new CCGT investments.

Between the minimum cost solution and the minimum CO_2 solution an increase of about 7.4 €/MWh (0.74 cents/kWh) of the average generation cost may be expected. For the sake of comparison and taking into consideration that in January 2006, the electricity price paid by an average domestic consumer was 14 cents/kWh, this additional cost represents about 5% of the current domestic electricity price[66]. On the other hand, theoretically it would be possible to prevent the production of about 0.4 tonCO_2/MWh, although this value corresponds to an academic solution based on the total displacement of coal and old CCGT.

Under the EU burden sharing agreement, Portugal agreed to limit the GHG emissions. Between 2008 and 2012, National GHG emissions should not increase by more than 27% from the 1990 levels. To achieve this target Portugal must put in place policies and

[66] This value is close to ones obtained for other studies in UK. Strbac et al. (2007) concluded that if wind electricity generation represented about 20% of the overall UK electricity consumption, net additional costs would reach about 5% of the current domestic electricity price. Also Dale et al. (2004), results indicate that if almost 20% of electricity consumption in UK were produced by wind turbines the additional cost would be a little under 5% the average domestic unit price.

measures to prevent further increase of GHG emissions. Other Kyoto mechanisms, for example the carbon "sink" in the land use and forestry may be used to offset emissions and the possibility of emissions purchase also exists under emission trading schemes.

In 1990, the CO_2 equivalent emissions from the Public Electricity and Heat Production sector achieved about 14 Mton. Assuming a 27% increase, the maximum allowable average values for inland Portugal could reach about 17 Mton per annum. However, in 2005 the emissions from this sector were already 21 Mton.[67] According to the projections reported under the National Plan for the Climate Change in 2010 the CO_2 emission may be close to 19 Mton[68] if additional measures to reduce GHG emissions are meanwhile implemented. Some of these measures have direct impact on the electricity generation sector activity, namely the reduction on final electricity consumption and the reduction of grid losses. The report projects already the use of other Kyoto mechanisms and the emission purchase, to achieve the GHG target for Portugal. According to this, and taking into consideration that at this stage of the model the demand projections are based on REN's (2005) forecasts, it was decided to assume solution S4 as the Kyoto reference scenario, equivalent to an average value of CO_2 emissions equal to 20 Mton per year, for the 10 years planning period.

Considering solution S4, the average cost increase over the minimal cost solution is about 5.1% but the CO_2 emissions are reduced by about 36%. This solution exceeds the RES minimum limit and, at the same time, reduces the external dependency of the electricity sector comparatively to the minimal cost solution contributing also to the equilibrium between coal and gas technologies in the Portuguese electricity system.

The EPM and the corresponding results assume an average CO_2 emission factor and average specific fuel consumption for each technology, thus presuming that regardless of the operating conditions of the thermal power plants the average CO_2 emissions and fuel consumption for each MWh produced remain constant. However, clearly this is a simplification of the reality frequently used in electricity planning models (see for examples Cormio et al., 2003 and Linares and Romero, 2000) that allows the reduction of the computational effort by working only with linear functions. The next section of this

[67] Source: EEA (2007).

[68] Source: National Plan for the Climate Change, published in Resolution of the Ministries 104/2006. Assuming that CO_2 emissions represent 96% of the total GHG emissions for the electricity sector.

chapter deals with this issue and proposes a new non linear model to incorporate the influence of the operating conditions of thermal power plants on the respective efficiency, fuel consumption and emissions levels.

V.6 The impact of wind power on the electricity planning

The objective of this section is to study the effect of increasing wind generation on power system operation performance, analyzing the impact on cost, fuel consumption and CO_2 emissions. Adding new wind power to the system leads to a reduction of the electricity generation from other power plants and, depending on the characteristics of the electricity system, this may lead to great or moderate reduction of the CO_2 emissions and of fuel consumption.

If the electricity supplied by increasing wind power capacity replaces coal power production this may result in considerable CO_2 abatement. However, as pointed out by Holttinen and Tuhkanen (2004), for some countries wind could replace other production forms, like gas or even other renewable production forms. For the Portuguese case, particular attention must be paid to the role of the hydro sector and how it will be affected. It is essential to look at the system's response to a long period of wind power production, because as underlined by Holttinen and Tuhkanen (2004), even if the hydro production is reduced instantaneously, the hydro power stored in the reservoirs may replace fossil fuel power production at a later stage. To assess the true costs and the true emission gains derived from adding wind power to the system, a simulation of the entire system for a long period must be conducted.

V.6.1 The Portuguese electricity system under different wind scenarios[69]

To assess the impact that increasing wind capacity may have on the operating conditions of the Portuguese electricity system, REN was contacted and agreed to collaborate with this study and to run the exploration planning software for the Portuguese power market under different wind scenarios according to the researcher request[70]. The simulation was run assuming a one year period and the running/dispatch of the production units was obtained

[69] Part of the information presented in sections V.6.1 to V.6.4 was published in a previous paper from the authors Ferreira et al. (2007c).
[70] The authors wish to express their gratitude to REN for their interest and collaboration on this work.

for different values of installed wind power. For simplicity reasons, the installed power of the other plants was set equal to the one expected under REN (2005) scenarios for 2016 and the electricity expected demand was based also on REN (2005) growth forecasts.

The results were described by the power output of each power station for four previously defined "hourly steps"[71] of each week. The model assumed the possibility of exportation to Spain and was based on the operating costs of each power production plant, on their technical constraints, on the historical hydro inflows, on the water values for each hydro storage plant and on the historical load factor of the wind power plants. Theoretically, this study assumes that different wind scenarios do not influence the installed power of the rest of the system. This results in an increase of the production capacity for large wind scenarios, which may explain the net exports increase.

From the REN data, the average load level of each power plant was computed during one year according to equations 5.28 and 5.29.

$$\overline{P}_x = \frac{\left[\sum_{j=1}^{4}\sum_{n=1}^{52} HS_j P_{sj,x}\right]_{\in P_{sj,x} \neq 0}}{\left[52\sum_{j=1}^{4} HS_j\right]_{\in P_{sj,x} \neq 0}} \qquad (5.28)$$

$$\overline{LL}_x = \frac{\overline{P}_x}{IP_x} \qquad (5.29)$$

where $\overline{P}_x$ is the average power output of plant x during the analysed year; HS_j is the number of hours of hourly step j; $P_{sj,x}$ is the average power output of plant x during the hourly step j of week s; $\overline{LL}_x$ is the average load level of power plant x during the analysed year and IP_x is the installed power of plant x.

[71] Hourly steps of the week represent the average power output of each power plants for the: 8 peak hours of higher electricity consumption in the week (HS1), following higher 72 hours (HS2), following higher 26 hours (HS3) and 62 hours of lower electricity consumption in the week (HS4).

For the computation of the average power output value only the power output of the plants with production different from zero in each hourly step were included, meaning that it computes the average production regime of the working plants and the value is not affected by the non operational periods. Thus the average load level is the measure of the annual energy that the unit produces compared to the maximum possible production that could be obtained if the unit would be operating at full load whenever called to the system[72].

The model running was conducted assuming four different wind power scenarios in 2016:

- Low growth (W1): installed wind power equal to 2000 MW. Assuming a wind capacity utilisation factor of 26%, wind generation will produce 5.5% of the Portuguese electricity consumption in 2016.

- Moderate growth (W2): installed wind power equal to 3500 MW. Assuming a wind capacity utilisation factor of 26%, wind generation will produce 9.7% of the Portuguese electricity consumption in 2016.

- Reference scenario (W3): installed wind power equal to 4750 MW. Assuming a wind capacity utilisation factor of 26%, wind generation will produce 13% of the Portuguese electricity consumption in 2016.

- High growth (W4): installed wind power equal to 7700 MW. Assuming a wind capacity utilisation factor of 26%, wind generation will produce 21% of the Portuguese electricity consumption in 2016.

V.6.1.1 Results of the exploration planning of the Portuguese electricity system

The results of the exploration planning of the Portuguese electricity system in 2016 inidicated that CCGT would be the most affected thermal power plants by the increase of

[72] The average load level and the load factor of a particular power plant for a given period represent then two different measures. The average load level describes the operating regime of the power plant when ever it is called to system and it remains unaffected by the non operational period. The load factor describes the level of utilisation of the power plant and it is affected by the non operational periods.

For an year period (8760h): Load factor= $\frac{\text{Energy produced by unit k during year t}}{\text{Power of unit k} \times \text{8760 h}}$

For an year period (8760h): Load level= $\frac{\text{Energy produced by unit k during year t}}{\text{Power of unit k} \times \text{number of effective operating hours in year t}}$

wind power in the system. According to the REN study information, increasing the installed wind power may lead to a reduction of the load level of the CCGT and also to a reduction of the number of operating hours. Coal power plants would be operating close to full load regardless of the installed wind power, although the number of operating hours would be slightly reduced for large wind scenarios. These results are consistent with the European Wind Integration Study (UCTE, 2007b) According to this study a large increase in installed wind power in Portugal would result mainly in the reduction of gas power production but the coal power plants would remain almost unaffected.

Figure 5.7 presents the expected average load level for a set of CCGT plants expected to be present in the system in 2016. The computations included only the power plants for which disaggregated information for each individual power group was available. For confidentiality reasons, only the average values are presented and the load level (LL) of each CCGT plant is not reported. For the same reason, this thesis does not detail the information obtained for each one of the power plants during the 52 weeks, and presents only the aggregated results.

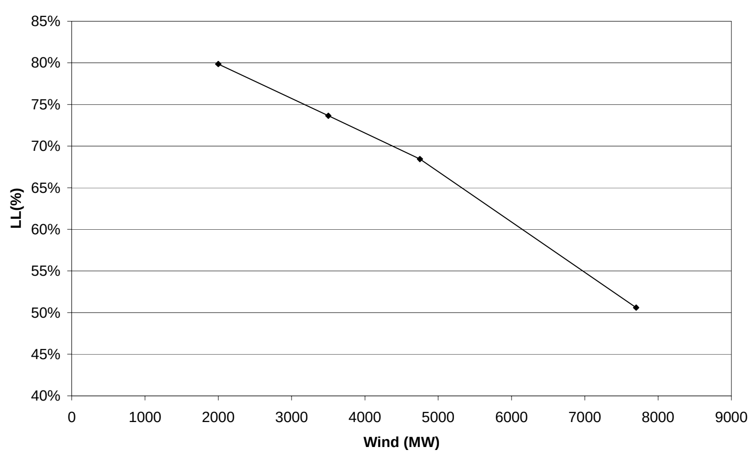

Figure 5.7–Results for CCGT load level (LL), when adding wind power to the Portuguese system. Source: Own elaboration of REN data.

The visual observation of the plot seems to indicate that a linear model may describe properly the data for the analysed power plant. Equation 5.30 presents this linear regression analysis, including the statistical significance of the results.

$$\overline{\mathrm{LL}}_{\mathrm{CCGT}} = -5.178 \times 10^{-5}\ \mathrm{IP_w} + 0.914 \quad \text{for } 1515 < \mathrm{IP_W} < 9000 \tag{5.30}$$

$$\qquad (-13.6)^* \qquad (48.4)^*$$

$R^2 = 0.99$

F statistic=184.7

where $\overline{\mathrm{LL}}_{\mathrm{CCGT}}$ is the average load level of the CCGT plants operating in the system during the analysed year and $\mathrm{IP_W}$ (MW) is the installed wind power in the system in the analysed year. R^2 is the regression coefficient. The number in brackets are the t-statistics and * indicates statistical significance at the 95% level. The equation is assumed to be valid for values of installed wind power between the present value (1515 MW) and the maximum level established by equation 5.27 (9000 MW).

The high regression coefficient value indicates a strong relationship between the installed wind power and the average load level of the CCGTs. The F statistic value is also high and largely exceed the critical value for this particular analysis ($F_{critical}$=18.51 for ν_1=1, ν_2=2 and 95% significance level), indicating the rejection of the hypothesis that all regression coefficients are zero. Each one of the individual regression coefficients presents statistical significance at the 95% level, according to the t –statistics ($t_{critical}$=4.303 for ν=2 and 95% significance level). These results confirm the statistical acceptance of the linear regression.

The results do not allow a conclusion on the effect of different wind scenarios on the number of start-ups of thermal powered units in Portugal. The ESB National Grid (2004) work concluded that the mid-merit plants of the Irish electricity system would be significantly affected, and to some extent also the base load units. However, it should be noted that the importance of the hydro sector in Ireland is much lower than in Portugal, not even reaching 10% of the total generating capacity.

The study for Denmark (Holttinen and Pederson, 2003) also indicates that increasing the penetration of wind in the system, would result in increasing the starts and stops of the thermal power plants. However, the effect would be reduced for larger wind shares due to the increased part load operation of the thermal plants. The connection to the Nordic market gives Denmark important flexibility on managing the power plants and the increase in the expected start-ups was not as high as in the Irish case.

In Portugal, the combination of wind power and hydro storage capacity may significantly reduce the negative impact that large wind power scenarios might have on the number of start-up and stops of thermal power plants. Unfortunately, the available data do not allow estimating the extent of this impact and, as such, the present model does take this aspect into account.

V.6.1.2 Impact of wind power on CCGT operating performance

The efficiency of thermal power plants depends on their operating regime, namely on the average load level and on the number of start ups. Works like Denny and O'Malley (2006) or Holttinen and Tuhkanen (2004) already drew attention to this issue, when analysing the effect of wind power production on the emissions from generation plants. Strbac et al. (2007) also reported that thermal power units operate less efficiently when part loaded, with higher losses in the case of gas plants. In addition, the ESB National Grid (2004) study on the impact of wind power generation on the operation of the Irish conventional plants concludes that the fuel costs of the thermal power plants do not decrease in proportion to their decrease in output, due to the increase start-ups and lower load level.

The flexible operation of a CCGT has significant implications for emissions, efficiency, plants lifetime and operational costs (Burdon, 1998). Kram et al. (2004a and b), presented an analysis of how operating constraints impact the efficiency and the financial gains of the combined cycle plants, focusing in particular on the number of start-ups and consequent increase on the variable operating and maintenance costs. Subsequently, Jackson (2005) reported that most CCGT are designed on the assumption that they would either be operated in baseload mode or infrequently cycled. Not doing so, leads to additional maintenance costs and outages time. Similar arguments were presented by Burdon (1998) for the UK, pointing out that the load following can lead to marginally shorter lifetimes or increase O&M expenditures. Maloney (2001) analysed conventional steam generating units in USA and concluded that generally, the average variable cost of these units show substantial economies as capacity utilization increases.

The shape of the characteristic curve of a CCGT has previously been reported by Kim (2004) and Lazzaretto and Carraretto (2005), demonstrating that the efficiency of these plants depends on their operating regime. It seems than, that the fuel consumption and the

CO_2 emission values are not linear functions of the output. Interviews conducted during this research with power plant managers currently operating CCGT and with specialists of the electricity sector, corroborate this statement. However, from these interviews and from literature review it was not possible to collect direct information on the mathematical function characterising the fuel consumption of these units.

Several companies operating CCGT in the Iberian market were then contacted and, one of them agreed to supply information on the hourly operating data for 2005[73]. The available data included the hourly output, the natural gas consumption and the CO_2 emissions of one of their power groups. Figure 5.8 presents the computed average hourly load level, the natural gas specific consumption and the CO_2 specific emissions.

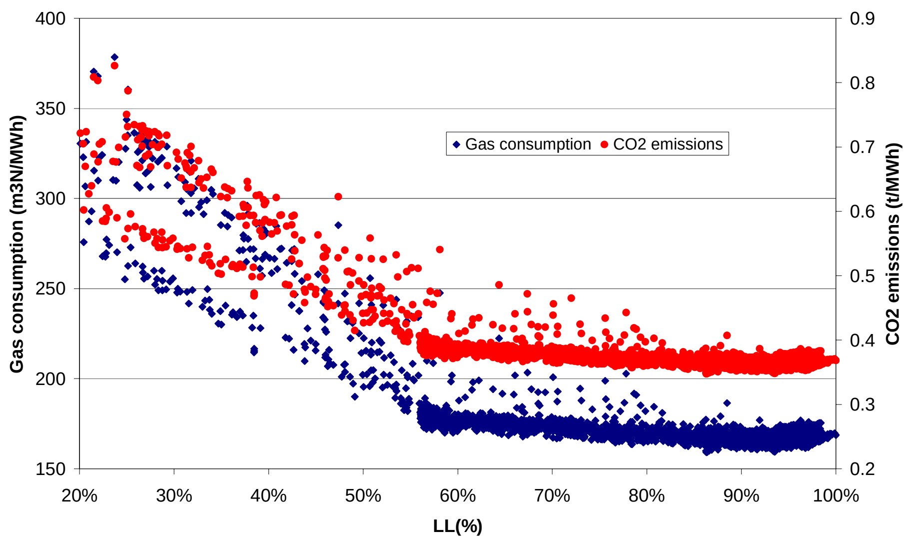

Figure 5.8 – Average hourly natural gas specific consumption and the CO_2 specific emissions.vs. load level of a CCGT.

The characteristic plot of this power plant group presents the expected shape according to Kim (2004) and Lazzaretto and Carraretto (2006), where the efficiency and load level curves for the CCGT technology were depicted.

Burdon (1998) describes the impacts of the low-load operation of a gas turbine. According to this author's experience, operating the gas turbines below a 60-70% load level results in much reduced efficiency, increasing the release of CO_2 per unit of electricity generated.

[73] The authors wish to express their gratitude to this company for their interest and collaboration on this work. For confidentiality reasons this power plant will not be identified.

Figure 5.8 demonstrates that for this particular plant, operating at a load level below 56% significantly reduces efficiency, consequently increasing the specific gas consumption and the specific CO_2 emissions.

Strbac et al. (2007) analysed the impact of wind generation on the operation and development of the UK electricity system. A linear relationship between the cost of electricity generated and load level was assumed. These authors supposed that both fuel consumption and CO_2 emissions increase linearly with the reduction of the operating load level, furthermore this increase would be about 20% between half- and full-load level. However, the visual observation of Figure 5.8 indicates that a quadratic model may describe the data for the CCGT analysed in the present study better, even for the Strbac et. al. (2007) range (half-full load). The figure also indicates that during most of the time the plant is operating at a load level beyond 56%, which falls within the linear range of the characteristic curve. However, according to the bounds set for equation 5.30 the average load level of the CCGT will range between 84% (for IP_W=1515) and 45% (for IP_W = 9000 MW), a value outside the linear range of the curve.

According to the empirical data, the gas consumption and CO_2 emissions increase between half- level and full-load is about 28%. Nevertheless, for the Portuguese system under analysis, the estimated increase between the minimum and maximum wind power in the system reaches 37% due to the non linearity of the characteristic curve. Taking these limits into account, the quadratic relationship seems to give a better mathematical description of the characteristic curve of the CCGT and allows for the generalisation of the model.

Combining these observations with the regression analysis presented in equation 5.30, mathematical functions relating installed wind power and the specific fuel consumption and specific CO_2 emissions were derived. Figure 5.9 summarises the full procedure.

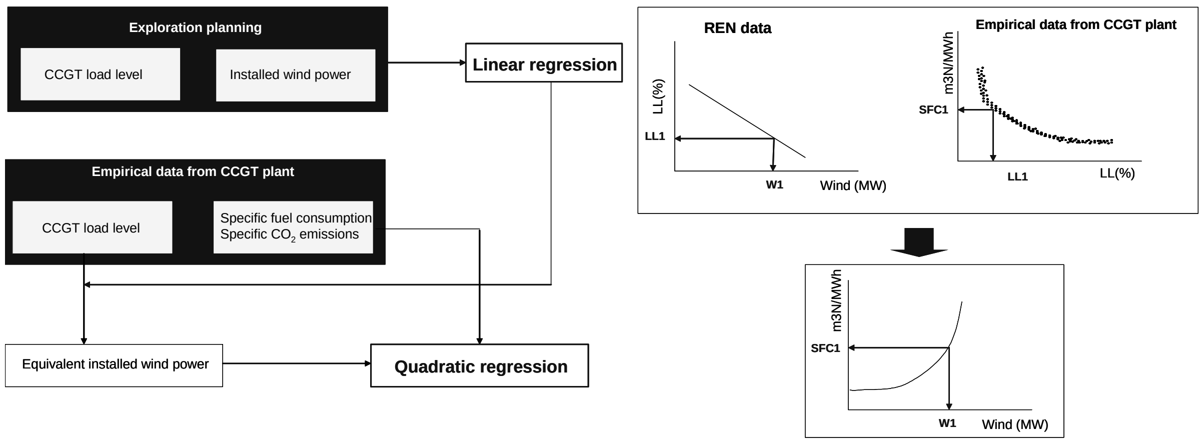

Figure 5.9- Computation of the relationships between installed wind power and the specific fuel consumption (SFC) of CCGT.

The process started with the computation of the linear relationship between average CCGT load level and installed wind power in the system (equation 5.30). Using this relationship and the empirical data obtained from the real CCGT, it was possible to compute the installed wind power theoretically equivalent to each empirical load level. These values represent the expected average load level of the CCGT operating in the Portuguese system for different values of wind power, ranging between 1515 and 9000 MW. From this, a quadratic function relating the theoretically installed wind power with the specific fuel consumption of the CCGT was obtained. The process was repeated, now relating the CO_2 emissions with the installed wind power in the system. Equations 5.31 and 5.32 present these quadratic regression analyses, including the statistical significance of the results.

$$\underset{}{\mathrm{SFC}\,(\mathrm{m^3N/MWh})} = \underset{(128.1)\,*}{1.10\times10^{-6}\ \mathrm{IP_w}^2} - \underset{(-53.2)\,*}{3.79\times10^{-3}\ \mathrm{IP_w}} + \underset{(1701.1)\,*}{165.8} \qquad \text{for } 1515 < \mathrm{IP_W} < 9000$$

$$R^2 = 0.84 \qquad (5.31)$$

F statistic=19511

$$\mathrm{COEF}\,(\mathrm{ton/MWh}) = \underset{(128.1)\,*}{2.41\times10^{-9}\ \mathrm{IP_w}^2} - \underset{(-53.1)\,*}{8.28\times10^{-6}\ \mathrm{IP_w}} + \underset{(1701.1)\,*}{0.362} \qquad \text{for } 1515 < \mathrm{IP_W} < 9000$$

$$R^2 = 0.84 \qquad (5.32)$$

F statistic=19511

where SFC is the specific gas consumption of the CCGT plants in the system(m^3N/MWh), IP_W is the installed wind power in the system in the analysed year (MW) and COEF is the specific CO_2 emissions of the CCGT plants in the system (ton/MWh). R^2 is the regression coefficient. The number in brackets are the t-statistics and * indicates statistical significance at 95% level. The equations are valid for values of installed wind power between the present value (1515 MW) and the maximum level established in equation 5.27 (9000 MW).

Equations 5.31 and 3.32 describe the theoretical relationship between the specific fuel consumption and the CO_2 emission factor of an existing CCGT and the installed wind power in the system. For the new CCGT it was assumed that the shape of the relationship would be the same, but the expected higher efficiency[74] leads to new functions described in equations 5.33 and 5.34.

$$\mathrm{SFC}\,(\mathrm{m^3N/MWh}) = 1.04\times10^{-6}\,\mathrm{IP_w}^2 - 3.56\times10^{-3}\,\mathrm{IP_w} + 155.8 \qquad \text{for } 1515 < \mathrm{IP_W} < 9000 \tag{5.33}$$

$$\mathrm{COEF}\,(\mathrm{ton/MWh}) = 2.26\times10^{-9}\,\mathrm{IP_w}^2 - 7.78\times10^{-6}\,\mathrm{IP_w} + 0.340 \qquad \text{for } 1515 < \mathrm{IP_W} < 9000 \tag{5.34}$$

These load-dependent efficiency curves must be included in the planning model to adequately account for partial load situations. Equations 5.31-5.34 allow to address the loss of efficiency of the CCGT system as a whole with the increasing wind penetration levels. Thus, these characteristics curves do not intend to represent any particular power plant but rather try to establish a possible relationship between wind power and the operating conditions of the existing and new CCGT systems in Portugal.

V.6.1.3 Impact of wind power on CO_2 emissions

The quantity of CO_2 emitted by the electricity generation sector depends directly on the thermal power plants production and on the type of fuel being burned. As analysed before, the efficiency and consequently the emissions from fossil fuel fired generators are strongly

[74] According to Tables 5.1 and 5.4, the average efficiency of new CCGT is expected to be 57% and the average efficiency of existing CCGT is 54%. For simplicity reasons, it was assumed that the 0.54/0.57 relationship would hold regardless of the output or load level of the power plants.

affected by the operation regime of the plants. The quantification of the emission saving from an increasing share of wind power, must take this negative effect into account.

To analyse the impacts of increasing wind power levels in the Portuguese electricity grid, data from REN study was used. The obtained exploration plans for different wind scenarios were based on the variable cost of the system, taking into consideration operational constraints and assuming the possibility of transmissions between Portugal and Spain. For the operating costs, 2005 values were used and the expected market prices for the exchanges with Spain were also based on 2005 values.

Figure 5.10 presents the results of the simulation for 2016, including the transmission balance (exports-imports) and the electricity generation in Portugal, for the four wind power scenarios previously described. According to this study, adding wind to the system will result in an increase of the electricity exports to Spain. The results also indicate that wind power will not replace hydro power, since the hydro production levels will remain more or less the same, regardless of the available wind power in the system. This way, a clean energy form will not replace another RES and emissions free electricity production technology.

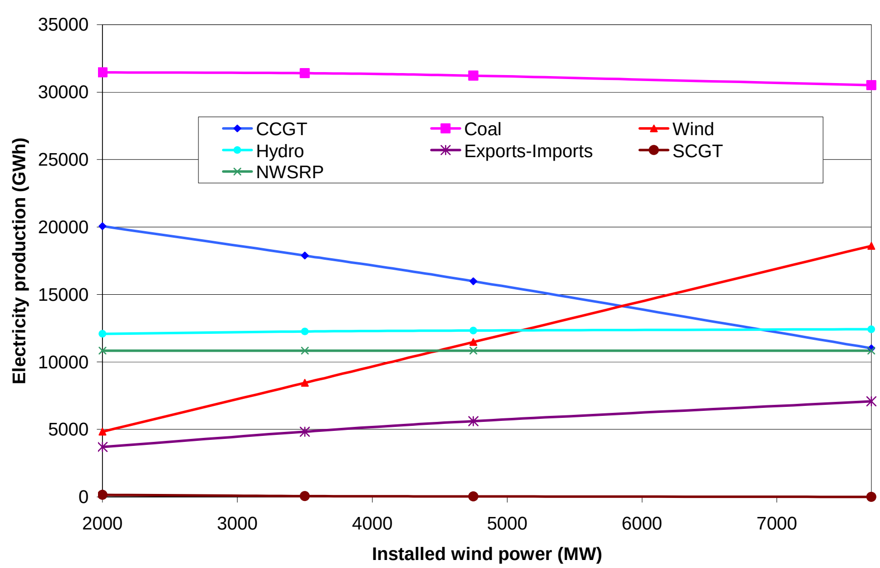

Figure 5.10- Electricity generation by technology and import-export balance for 2016, for different wind scenarios in the Portuguese system. Source: Own elaboration of REN data.

The increase of wind power capacity will most significantly affect the operating conditions of the natural gas power plants, leading to a reduction of both average load level and number of operating hours of the CCGT plants.

Equation 5.35 represents the expression used for the computation of the decrease in average CO_2 emissions for wind scenario Wi (2-moderate growth, 3-reference and 4-high growth) over the low growth wind scenario (W1). As seen in Figure 5.10, the increase of wind power will result in an overall increase of the electricity produced, due to the possibility of exports to Spain. Therefore, in order to compare different wind scenarios, the values of CO_2 emissions per MWh of the different situations must be used instead of absolute values.

$$CO_2 \text{ reduction } (\%) = \frac{\left\{ \dfrac{\sum_x \sum_{j=1}^{4} \sum_{s=1}^{52} HS_j P_{sj,x} COEF_{sj,x}}{\sum_x \sum_{j=1}^{4} \sum_{s=1}^{52} HS_j P_{sj}^{x}} \right\}_{W1} - \left\{ \dfrac{\sum_x \sum_{j=1}^{4} \sum_{s=1}^{52} HS_j P_{sj,x} COEF_{sj,x}}{\sum_x \sum_{j=1}^{4} \sum_{s=1}^{52} HS_j P_{sj,x}} \right\}_{Wi}}{\left\{ \dfrac{\sum_x \sum_{j=1}^{4} \sum_{s=1}^{52} HS_j P_{sj,x} COEF_{sj,x}}{\sum_x \sum_{j=1}^{4} \sum_{s=1}^{52} HS_j P_{sj,x}} \right\}_{W1}} \times 100 \qquad (5.35)$$

$$\text{for } i = 2,3,4$$

where HS_j is the number of hours of hourly step j; $P_{sj,x}$ is the average power output of plant type x during the hourly step j of week s; $COEF_{sj,x}$ is the specific CO_2 emission factor of power plant x for the hourly step j of week s. $P_{sj,x}$ values were obtained from REN study. $COEF_{sj,x}$ values were obtained from: (i) the quadratic equations relating the load level with specific CO_2 emission factors of the new and existing CCGT, presented in Annex 8; (ii) average CO_2 emission factors for the SCGT, for the coal power plants and for the cogeneration power plants (from Tables 5.1 and 5.4).

The CO_2 abatement of wind power may be computed from the reduction of CO_2 emissions per unit of electricity produced from wind. The CO_2 savings result from the reduction of fuel that would be consumed in thermal power plants under reduced wind power alternatives. Table 5.10 presents the average CO_2 emissions of the system per unit of electricity produced, the CO_2 reduction over the low growth wind scenario computed from equation 5.35 and the CO_2 abatement of wind power under the low growth wind scenario.

Table 5.10- CO_2 abatement of wind power over the low growth wind scenario for 2016.

Wind scenario (MW)	**Average CO_2 emissions (Mton/MWh)**	**CO_2 reduction (%)**	**CO_2 abatement of wind power (ton/MWh_w)[1]**
2000	0.429	--	--
3500	0.411	4.1%	0.218
4750	0.397	7.5%	0.235
7700	0.363	15.4%	0.276

[1] MWh_w- electricity produced from wind

According to the results, the CO_2 emissions decrease almost linearly with the increasing wind power capacity. Also, the CO_2 abatement of wind power increases as wind power penetration gets higher. This is due to the reduction of the share of electricity produced by CCGT plants and, for large wind scenarios (W4), the results of the simulation indicate an additional reduction of coal power production. Thus, it seems that in the Portuguese electricity system, the environmental gains of increasing wind power capacity can overcome the decreasing efficiency of thermal power plants even for large wind power scenarios.

The CO_2 abatement of wind power over the low growth wind scenario was also computed assuming average COEF for the CCGT power plants independent of the load level (using values drawn from Tables 5.1 and 5.4). The values were higher than the ones reported in Table 5.10 and ranged between 0.240 ton/MWh_w and 0.296 ton/MWh_w. This result indicates that the CO_2 abatement computation is favoured when using average values and when no load dependent efficiency curves are taken into account.

V.6.1.4 Impact of wind power on the operating cost of the electricity system

Based on exploration planning results, the cost implications of the increasing wind power scenarios were also addressed. The values of the operating costs were derived from the expected output of each power plant obtained from REN study.

Equation 5.36 represents the expression used for the computation of the decrease in average operating costs for wind scenario Wi (moderate growth, reference and high growth) over the low growth wind scenario (W1). Due to the added exports, once more the average cost values were used instead of absolute values.

$$\text{Cost reduction (\%)} = \frac{\left\{\dfrac{\sum_{x}\sum_{j=1}^{4}\sum_{s=1}^{52}\left[HS_j P_{sj,x}\left(SFC_{sj,x}\times Fuel_x + VOM_x + COEF_{sj,x}\times EC\right)\right]}{\sum_{x}\sum_{j=1}^{4}\sum_{n=1}^{52} HS_j P_{nj,x}}\right\}_{W1} - \left\{\dfrac{\sum_{x}\sum_{j=1}^{4}\sum_{s=1}^{52}\left[HS_j P_{sj,x}\left(SFC_{sj,x}\times Fuel_x + VOM_x + COEF_{sj,x}\times EC\right)\right]}{\sum_{x}\sum_{j=1}^{4}\sum_{s=1}^{52} HS_j P_{sj,x}}\right\}_{Wi}}{\left\{\dfrac{\sum_{x}\sum_{j=1}^{4}\sum_{s=1}^{52}\left[HS_j P_{sj,x}\left(SFC_{sj,x}\times Fuel_x + VOM_x + COEF_{sj,x}\times EC\right)\right]}{\sum_{x}\sum_{j=1}^{4}\sum_{s=1}^{52} HS_j P_{sj,x}}\right\}_{W1}} \times 100$$

$$\text{for } i = 2,3,4 \qquad (5.36)$$

where HS_j is the number of hours of hourly step j; $P_{sj,x}$ is the average power output of plant type x during the hourly step j of week s; $SFC_{sj,x}$ is the specific fuel consumption of power plant x for the hourly step j of week s; $Fuel_x$ is the fuel cost of power plant x; VOM_x is the average variable O&M costs of power plant x and $COEF_{sj,x}$ is the specific CO_2 emission factor of power plant x for the hourly step j of week s and EC is the CO_2 emissions cost. $P_{sj,x}$ values were obtained from REN study. $SFC_{sj,x}$ values were obtained from: (i) the quadratic equations relating the load level with specific fuel cost of the new and existing CCGT, presented in Annex 8; (ii) average specific fuel costs for the SCGT, for the coal power plants presented in Tables 5.1 and 5.4[75]. $COEF_{sj,x}$ values were obtained as described for equation 5.35. Fuel costs are presented in Table 5.5.

The value of wind power may be computed from the cost reduction per unit of electricity produced from wind. The avoided costs result from: the reduction of fuel that would be consumed by thermal power plant, the consequent reduction of emission costs, and also from the reduction of the variable O&M costs. Table 5.11 presents: the average operating cost per unit of electricity produced, the operating cost reduction computed from equation 5.36 and the value of wind power over the low growth wind scenario. For the computation of the value of wind power, the operating costs were corrected, assuming that the export price is equal to the average operating cost.

[75] The operating costs of the NWSRP was not taken into consideration due to the unavailability of data for cogeneration. This should not be a major source of concern, since the production from NWSRP will remain unchanged for the four wind scenarios.

Table 5.11- Value of wind power over the low growth wind scenario for 2016.

Wind scenario (MW)	Average operating cost (€/MWh)	Operating cost reduction (%)	Value of wind power (€/MWh$_w$)[1]
2000	26.9	--	--
3500	24.9	7.6%	34.7
4750	23.3	13.5%	34.9
7700	19.6	27.2%	36.5

[1] MWh$_w$- electricity produced from wind

According to the results, the electricity production cost reduces almost linearly with the increasing wind power capacity. Also, the value of wind power increases as wind power penetration gets higher. Once more, the economic gains obtained with the reduction of fossil fuel consumption still compensate the loss of efficiency of thermal power plants, even for large wind power scenarios.

The value of wind power over the low growth wind scenario was also computed assuming average SFC and average COEF for the CCGT power plants independent of the load level (values drawn from Tables 5.1 and 5.4). The obtained values ranged between 37.9 €/MWh and 38.8 €/MWh, indicating once more that using average values leads to the overestimation of the value of wind power in comparison to values obtained using load dependent efficiency curves.

V.6.1.5 Comparison of the results with other studies.

Previous works have already addressed the impact that increasing wind power levels may have on the operating conditions of an electricity system. The ESB National Grid (2004) study focused on this issue for the Irish electricity system and analysed the impact of the increasing number of start-ups and of the lower capacity factor of the conventional plants, as the wind power increases. The Holttinen and Pederson (2003) and Holttinen and Tuhkanen (2004) studies analysed the effect of large scale wind power on thermal power system operation and electricity exchanges in the Nordic electricity market.

The results obtained for the Portuguese system, indicate that the increasing of the wind power electricity production would lead to a significant increase of the electricity exports to Spain. However, the net exchange increases at a much lower rate than the wind power electricity generation, as may be seen in Figure 5.10. Thus, in contrast to the Holttinen and Pederson (2003) study for West Denmark, the major part of the wind power production will not flow abroad and will be used to meet internal consumption.

The Holttinen and Pederson (2003) results for West Denmark and the Rosen et al. (2007) results for Germany, indicated that the CO_2 abatement would be reduced as wind power penetration gets higher. The different configuration of the Portuguese system justifies part of the somewhat different values obtained for Portugal. The Danish and German studies concluded that wind power would mainly replace coal and only in a latter stage would replace more efficient CCGT units. However, REN study information indicates that in Portugal wind power will mainly replace CCGT electricity production and, coal power plants production will only be affected in case of large wind power scenarios. In addition, increasing wind power leads to higher electricity exports, the amount of electricity generated by wind plants will not replace the same amount produced by thermal power plants and there will be an increase of the total electricity production. This fact offsets the possible reduction of the load level of CCGT and consequent loss of efficiency. Holttinen and Peddersen (2003) already highlighted this and concluded that when the transmission possibility was included, the CO_2 reductions were very modest when compared with the no transmission scenarios due to the added exports. These authors argue that the CO_2 abatement of wind power in an area that is part of a larger system is especially difficult to estimate.

The CO_2 abatement potential on the Portuguese electricity system seems to be lower than in the Irish case[76]. However, for the Portuguese situation this abatement is computed against the low wind scenario while in the Irish case the abatement is computed against the non wind case. Higher CO_2 reduction values were also obtained for Nordic countries cases (Holttinen and Tuhkanen, 2004). The authors concluded that wind power increase would replace mainly electricity generated by coal fired plants, resulting in a CO_2 abatement potential close to 0.7 ton/MWh for both the Nordic and Finish system. However, when assuming that coal condensing power was no longer used in Finland, new wind power would replace mainly CCGT capacity reducing significantly the CO_2 abatement potential to less than 0.3 ton/MWh. As for the German system the estimated CO_2 abatement potential ranged between 0.69 ton/MWh and 0.37 ton/MWh (Rosen et al. 2007). According to the authors, the ecological benefits decreased with the growing share of wind power not

[76] ESB National Grid (2004) results indicate that the CO_2 abatement potential of wind power generation would reach 0.321 ton/MWh_w for 20% wind energy penetration.

only due to the reduced fuel efficiency, but also because wind energy substituted CO_2-free electricity production from nuclear power plants.

As with the CO_2 abatement case, the value of wind power in Portugal shows an increasing trend with increasing wind power shares. Once more these results are different from the ones obtained in Holttinen and Pedersen (2003) and Rosen et al. (2007) studies, who observed important reductions on the value of wind power as wind penetration gets higher. However, the Holttinen and Pedersen (2003) results also indicate that for high transmission scenarios the decrease of the value of wind power was much smaller.

In general, the wind power value of the Portuguese electricity system seems to be higher than the values obtained in other European studies. Holttinen and Pedersen (2003), concluded that the value of wind power for West Denmark when operating with out exchanges laid between 19 and 15 €/MWh_w (between 10 and 40% wind penetration). For the German system, Rosen et al. (2007) estimated that the value of wind power could reach values between 14 and 11€/MWh_w. As wind power is Portugal is expected to replace mainly CCGT electricity production, the emission gains may not be as high as the ones reported for these studies where coal electricity production is the most affected, but the obtained cost savings are higher reflecting the high natural gas prices verified in 2005.

Finally, it should be underlined that the results are strongly affected by the transmission possibility. Energy exchanges with Spain allow for levelling out the variations in electricity production, so that the thermal power plants operating regime is not affected as much by wind power as it would have been without transmission. In fact, if the transmission possibility was ruled out or significantly reduced, a reduction of the thermal power output can be expected, which would affect both the load level and the number of operating hours.

V.6.2 Model formulation

A new planning model was designed to include the impact of wind power on the operating performance of the thermal power plants. This new model follows the same structure of the linear EPM described in previous sections. The only differences lay in the cost and emission objective functions, where the gas cost and specific emission factors for the CCGT will no longer be parameters but rather auxiliary variables depending on the installed wind power. The constraints will be set equal to the ones described in section V.3.4.

According to the analysis previously conducted in Section V.6.1, for the inclusion of new functions relating specific fuel consumption and the CO_2 emission factor of the CCGT, some underlying assumptions had to be considered, namely:

- The model deals with the CCGT system and not with individual power plants. Thus, the individual performance and operating regime of each power plant are not taken into consideration. Only two subsystems are considered: the existing CCGT and the new CCGT, each one described by average curves defined by equations 5.31-5.34

- If only average functions were used to describe the CCGT subsystem, the model would be implicitly assuming that all groups would be operating at the same load level in each moment and this load would remain constant during each interval of the planning period (month). In reality, there is a merit order ranking different technologies and power plants and their load will vary during each interval. For setting the dispatch and managing real time load balancing, the manager of the system defines the load assigned to each power plant according to a list of operating parameters that characterise the plants available for dispatch, namely, minimum and maximum capacity, heat rate curve, start up costs, start up time, amongst others[77]. In order to tackle this problem, the model assumes a theoretical distribution of the load for the CCGT system during the planning period, as follows[78]:

    - each CCGT subsystems will be operating at average load levels (characterised by equations 5.31-5.34) to produce 50% of their electricity supply during each interval of the planning period;
    - each CCGT subsystems will be operating at a load level 10% higher than the average to produce 25% of their electricity supply during each interval of the planning period;

[77] The short term planning process is described in detail in Mazer et al. (2007).
[78] The problem of assuming load distribution instead of using average functions is longer debated in Annex 9.

- each CCGT subsystems will be operating at a load level 10% lower than the average to produce the remaining 25% of their electricity supply during each interval of the planning period;

➢ The extent of the impact of the installed wind power on the CCGT load level is based on data obtained from the theoretical REN study for a set of CCGT's operating in the system in 2016 and described by equation 5.30. This study's assumptions are, of course part of the base pre-requisites of the optimisation model:

  - The study theoretically assumes that different wind scenarios do not influence the installed power of the remaining system. The study is then based on a fixed hydro and thermal power system combined with different wind power scenarios.

  - REN study includes the possibility of electricity exports to Spain. However, the aim of the optimisation model is the search for an optimal electricity plan to meet internal demand and, as such, the electricity exports are not accounted for in the optimisation process. By integrating equation 5.30 in the optimisation model, it is implicitly assumed that for each optimal power plan obtained, it will be possible to achieve the conditions set under REN study. If in reality the exports are lower than the estimated values, a sharper reduction of the average load level of the power plants could be expected along with a reduction of the number of operating hours. Under those conditions, there might be some underestimation of the wind power impacts on the operating performance of the thermal power system.

➢ The optimisation model presupposes that a quadratic function can describe the characteristic curve of a CCGT. It is also assumed that the characteristic curve of a CCGT operating in the Iberian market can represent the general shape of the characteristic curves of the CCGT subsystems considered in the model and described in equations 5.31-5.34.

The basic assumptions of the linear EPM, described in section V.3.5, are also valid for this new model. In particular, the model does not deal with specific power plants but with technologies and no compensation payments are foreseen for reserve power plants.

Based on all these assumptions a Non Linear Electricity Planning Model (NLEPM) was obtained and is described in the next sections.

V.6.2.1 Cost objective

According to equations 5.31-5.34 and the assumed load distribution, the specific fuel consumption and CO_2 emission factor for the existing and candidate CCGT subsystems will be computed from equations 5.37 to 5.48.

25%[79]	$(SFC_{5t})_a = 1.10\times10^{-6}\,(IP_{9t}+IP_{3a,t}+IP_{3b,t})^2 + 4.66\times10^{-4}\,(IP_{9t}+IP_{3a,t}+IP_{3b,t}) + 162.6$ (5.37) $(COEF_{5t})_a = 2.41\times10^{-9}\,(IP_{9t}+IP_{3a,t}+IP_{3b,t})^2 + 1.02\times10^{-6}\,(IP_{9t}+IP_{3a,t}+IP_{3b,t}) + 0.355$ (5.38)
	$(SFC_{2t})_a = 1.04\times10^{-6}\,(IP_{9t}+IP_{3a,t}+IP_{3b,t})^2 + 4.38\times10^{-4}\,(IP_{9t}+IP_{3a,t}+IP_{3b,t}) + 152.8$ (5.39) $(COEF_{2t})_a = 2.26\times10^{-9}\,(IP_{9t}+IP_{3a,t}+IP_{3b,t})^2 + 9.60\times10^{-7}\,(IP_{9t}+IP_{3a,t}+IP_{3b,t}) + 0.336$ (5.40)
50%[80]	$(SFC_{5t})_b = 1.10\times10^{-6}\,(IP_{9t}+IP_{3a,t}+IP_{3b,t})^2 - 3.79\times10^{-3}\,(IP_{9t}+IP_{3a,t}+IP_{3b,t}) + 165.8$ (5.41) $(COEF_{5t})_b = 2.41\times10^{-9}\,(IP_{9t}+IP_{3a,t}+IP_{3b,t})^2 - 8.28\times10^{-6}\,(IP_{9t}+IP_{3a,t}+IP_{3b,t}) + 0.362$ (5.42)
	$(SFC_{2t})_b = 1.04\times10^{-6}\,(IP_{9t}+IP_{3a,t}+IP_{3b,t})^2 - 3.56\times10^{-3}\,(IP_{9t}+IP_{3a,t}+IP_{3b,t}) + 155.8$ (5.43) $(COEF_{2t})_b = 2.26\times10^{-9}\,(IP_{9t}+IP_{3a,t}+IP_{3b,t})^2 - 7.78\times10^{-6}\,(IP_{9t}+IP_{3a,t}+IP_{3b,t}) + 0.340$ (5.44)
25%[81]	$(SFC_{5t})_c = 1.10\times10^{-6}\,(IP_{9t}+IP_{3a,t}+IP_{3b,t})^2 - 8.05\times10^{-3}\,(IP_{9t}+IP_{3a,t}+IP_{3b,t}) + 177.3$ (5.45) $(COEF_{5t})_c = 2.41\times10^{-9}\,(IP_{9t}+IP_{3a,t}+IP_{3b,t})^2 - 1.76\times10^{-5}\,(IP_{9t}+IP_{3a,t}+IP_{3b,t}) + 0.387$ (5.46)
	$(SFC_{2t})_c = 1.04\times10^{-6}\,(IP_{9t}+IP_{3a,t}+IP_{3b,t})^2 - 7.56\times10^{-3}\,(IP_{9t}+IP_{3a,t}+IP_{3b,t}) + 166.5$ (5.47) $(COEF_{2t})_c = 2.26\times10^{-9}\,(IP_{9t}+IP_{3a,t}+IP_{3b,t})^2 - 1.65\times10^{-5}\,(IP_{9t}+IP_{3a,t}+IP_{3b,t}) + 0.364$ (5.48)

Where:

$(SCF_{5t})_a$ Specific gas consumption for generating 25% of electricity supplied by existing CCGT in each month of year t (m^3N/MWh).

$(SCF_{5t})_b$ Specific gas consumption for generating 50% of electricity supplied by existing CCGT in each month of year t (m^3N/MWh).

---

[79] In each month of year t, 25% of the electricity produced on the existing CCGT brings about a SFC drawn from equation 5.37 and a CO_2 emission factor drawn from equation 5.38.The same way, 25% of the electricity produced on the new CCGT brings about a SFC drawn from equation 5.39 and a CO_2 emission factor drawn from equation 5.40.

[80] In each month of year t, 50% of the electricity produced on the existing CCGT brings about a SFC drawn from equation 5.41 and a CO_2 emission factor drawn from equation 5.42.The same way, 50% of the electricity produced on the new CCGT brings about a SFC drawn from equation 5.43 and a CO_2 emission factor drawn from equation 5.44.

[81] In each month of year t, 25% of the electricity produced on the existing CCGT brings about a SFC drawn from equation 5.45 and a CO_2 emission factor drawn from equation 5.46.The same way, 25% of the electricity produced on the new CCGT brings about a SFC drawn from equation 5.47 and a CO_2 emission factor drawn from equation 5.48.

$(SCF_{5t})_c$	Specific gas consumption for generating the remaining 25% of electricity supplied by existing CCGT in each month of year t (m^3N/MWh).
$(SCF_{2t})_a$	Specific gas consumption for generating 25% of electricity supplied by candidate CCGT in each month of year t (m^3N/MWh).
$(SCF_{2t})_b$	Specific gas consumption for generating 50% of electricity supplied by candidate CCGT in each month of year t (m^3N/MWh).
$(SCF_{2t})_c$	Specific gas consumption for generating the remaining 25% of electricity supplied by candidate CCGT in each month of year t (m^3N/MWh).
$(COEF_{5t})_a$	CO_2 emission factor for generating 25% of electricity supplied by existing CCGT in each month of year t (ton/MWh).
$(COEF_{5t})_b$	CO_2 emission factor for generating 50% of electricity supplied by existing CCGT in each month of year t (ton/MWh).
$(COEF_{5t})_c$	CO_2 emission factor for generating the remaining 25% of electricity supplied by existing CCGT in each month of year t (ton/MWh).
$(COEF_{2t})_a$	CO_2 emission factor for generating 25% of electricity supplied by candidate CCGT in each month of year t (ton/MWh).
$(COEF_{2t})_b$	CO_2 emission factor for generating 50% of electricity supplied by candidate CCGT in each month of year t (ton/MWh).
$(COEF_{2t})_c$	CO_2 emission factor for generating the remaining 25% of electricity supplied by candidate CCGT in each month of year t (ton/MWh).

Combining these equations with equation 5.4 the total variable cost for the NLEPM may now be obtained from equation 5.49.

$$
\begin{aligned}
VC = & \sum_t \sum_h \sum_{k \neq 2} \left[\left(VOM_k + F_k + EC \times COEF_k \right) \times P_{kht} \times \Delta_h \times (1+i)^{-t} \right] \\
& + \sum_t \sum_h \sum_{l \neq 5} \left[\left(VOM_l + F_l + EC \times COEF_l \right) \times P_{lht} \times \Delta_h \times (1+i)^{-t} \right] \\
& + \sum_t \sum_h \left\{ \begin{bmatrix} VOM_2 \times P_{2ht} + (SFC_{2t})_a \times GC \times (0.25P_{2ht}) + EC \times (COEF_{2t})_a \times (0.25P_{2ht}) + \\ (SFC_{2t})_b \times GC \times (0.5P_{2ht}) + EC \times (COEF_{2t})_b \times (0.5P_{2ht}) + \\ (SFC_{2t})_c \times GC \times (0.25P_{2ht}) + EC \times (COEF_{2t})_c \times (0.25P_{2ht}) \end{bmatrix} \Delta_h \times (1+i)^{-t} \right\} \quad (€) \\
& + \sum_t \sum_h \left\{ \begin{bmatrix} VOM_5 \times P_{5ht} + (SFC_{5t})_a \times GC \times (0.25P_{5ht}) + EC \times (COEF_{5t})_a \times (0.25P_{5ht}) + \\ (SFC_{5t})_b \times GC \times (0.5P_{5ht}) + EC \times (COEF_{5t})_b \times (0.5P_{5ht}) + \\ (SFC_{5t})_c \times GC \times (0.25P_{5ht}) + EC \times (COEF_{5t})_c \times (0.25P_{5ht}) \end{bmatrix} \Delta_h \times (1+i)^{-t} \right\} \quad (5.49)
\end{aligned}
$$

Where GC is a parameter for the natural gas cost (€/m^3N). This value may be found in

Table 5.5, summarising the general assumptions under the base scenario. The first two terms of the equation are linear and represent the total variable cost of power plants excluding CCGT. The last two terms of the equation are non linear and represent the total variable cost of the CCGT.

The fixed cost will be obtained from equation 5.3 and the total cost equation may be described according to equation 5.50.

$$C = \sum_t \sum_k \left\{ \left[I_k \frac{i(1+i)^{nk}}{(1+i)^{nk}-1} + FOM_k \right] IP_{kt} \times (1+i)^{-t} \right\}$$

$$+ \sum_t \sum_h \sum_{k \neq 2} \left[\left(VOM_k + F_k + EC \times COEF_k \right) \times P_{kht} \times \Delta_h \times (1+i)^{-t} \right]$$

$$+ \sum_t \sum_h \sum_{l \neq 5} \left[\left(VOM_l + F_l + EC \times COEF_l \right) \times P_{lht} \times \Delta_h \times (1+i)^{-t} \right]$$

$$+ \sum_t \sum_h \left\{ \begin{bmatrix} VOM_2 \times P_{2ht} + \left(SFC_{2t}\right)_a \times GC \times \left(0.25P_{2ht}\right) + EC \times \left(COEF_{2t}\right)_a \times \left(0.25P_{2ht}\right) + \\ \left(SFC_{2t}\right)_b \times GC \times \left(0.5P_{2ht}\right) + EC \times \left(COEF_{2t}\right)_b \times \left(0.5P_{2ht}\right) + \\ \left(SFC_{2t}\right)_c \times GC \times \left(0.25P_{2ht}\right) + EC \times \left(COEF_{2t}\right)_c \times \left(0.25P_{2ht}\right) \end{bmatrix} \Delta_h \times (1+i)^{-t} \right\} \quad (€)$$

$$+ \sum_t \sum_h \left\{ \begin{bmatrix} VOM_5 \times P_{5ht} + \left(SFC_{5t}\right)_a \times GC \times \left(0.25P_{5ht}\right) + EC \times \left(COEF_{5t}\right)_a \times \left(0.25P_{5ht}\right) + \\ \left(SFC_{5t}\right)_b \times GC \times \left(0.5P_{5ht}\right) + EC \times \left(COEF_{5t}\right)_b \times \left(0.5P_{5ht}\right) + \\ \left(SFC_{5t}\right)_c \times GC \times \left(0.25P_{5ht}\right) + EC \times \left(COEF_{5t}\right)_c \times \left(0.25P_{5ht}\right) \end{bmatrix} \Delta_h \times (1+i)^{-t} \right\} \quad (5.50)$$

The final value obtained from this equation, corresponds to total cost of the electricity system for a 10 years planning period, taking into consideration the impact of wind power on the CCGT operating performance.

V.6.2.2 Emissions objective

The specific CO_2 emission factor for the CCGT will be computed from equation 5.38, 5.42 and 5.46 for the existing power plants and from equation 5.40, 5.44 and 4.48 for the candidate power plants. Combining these equations with equation 5.6, the total CO_2 emissions may be obtained:

$$CO = \sum_t \sum_h \sum_{k \neq 2} \left[\left(COEF_k \times P_{kht}\right) \times \Delta_h\right] + \sum_t \sum_h \sum_{l \neq 5} \left[\left(COEF_l \times P_{lht}\right) \times \Delta_h\right]$$

$$+ \sum_t \sum_h \left\{\left[\left(COEF_{2t}\right)_a \times \left(0.25P_{2ht}\right) + \left(COEF_{2t}\right)_b \times \left(0.5P_{2ht}\right) + \left(COEF_{2t}\right)_c \times \left(0.25P_{2ht}\right)\right]\Delta_h\right\} \quad \text{(ton)}$$

$$+ \sum_t \sum_h \left\{\left[\left(COEF_{5t}\right)a \times \left(0.25P_{5ht}\right) + \left(COEF_{5t}\right)_b \times \left(0.5P_{5ht}\right) + \left(COEF_{5t}\right)_c \times \left(0.25P_{5ht}\right)\right]\Delta_h\right\} \quad (5.51)$$

The first two terms of equation 5.51 are linear and represent the sum of the monthly emissions released by the power plants during the planning period excluding CCGT. The last two terms of the equation are non linear and represent the sum of the monthly emissions released by the CCGT during the planning period. The final value obtained from this equation corresponds to total CO_2 emissions expected to be released during the next 10 years, taking into consideration the impact of wind power on the CCGT operation.

V.6.2.3 Final considerations

Figure 5.11 shows the flow diagram for the NLEPM, including the input information, output results and the optimisation problem.

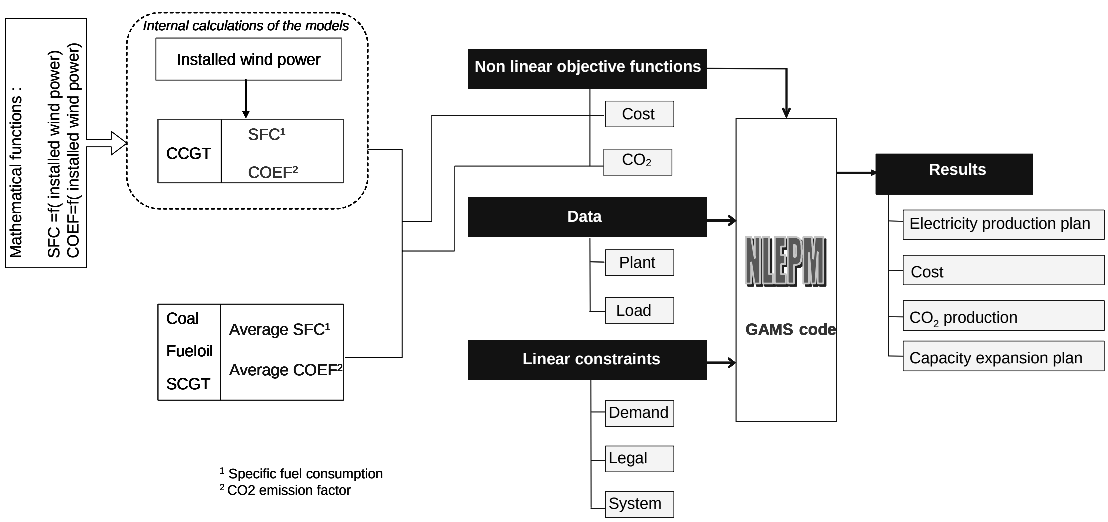

Figure 5.11- Non linear electricity planning model.

As with the EPM the input information for the problem includes the mathematical formulation of the objective functions and of the constraints. However, now the cost and

CO_2 objective functions are no longer linear. The input data still describes the technical and economic characteristics of the present and candidate power plants and the expected load pattern. This non linear model also assumes average specific fuel consumption and CO_2 emission factors for coal power plants, fueoil power plants and SCGT. The specific fuel consumption and CO_2 emission factors for the CCGT system are now based on empirical data and are described by quadratic functions relating these variables with the installed wind power.

V.6.3 NLEPM results

As the EPM, the NLEPM was written in a GAMS code and the Branch and Bound algorithm was used, calling BARON solver in order to ensure a global optimum for the problem. However, the dimension and complexity of the model led to some difficulties in the convergence process which was reflected mainly in the execution time. Karuppiah and Grossmann (2006) and Murray and Shanbhag (2007), already reported similar difficulties with BARON, such that to guarantee a global optimum for large problems this would mostly be reflected in the amount of computational time. As Bussieck et al. (2003) stated ".. an higher solution quality is often obtained at a cost of efficiency. Thus, users should consider if feasibility of the (local) solution and efficiency or global optimality at a cost of efficiency is the primary criteria."

To overcome these difficulties, BARON was used as a first approach to the problem, imposing a time limit and a maximum optimal tolerance of 0.025. Subsequently, local solver Standard Branch and Bound (SBB) was called upon to work out the problem, imposing zero optimal tolerance and setting the upper bound of the objective function equal to the value obtained with BARON optimisation. This ensures that the local solver is converging to the global optimum of the problem, and reduces significantly the necessary time to solve the problem.

SBB is a commercially available solver from Akri Software (SBB, no date). Some recent examples of studies using this solver include the optimisation of the energy management of a large-scale water supply network (Bounds et al. 2006), the optimisation of power production of small-scale CHP plants (Savola and Fogelholm, 2007) or the ECO-optimised reuse of processed liquors (Erol and Thoming, 2005).

Figure 5.12 represents the computational approach to the optimisation process.

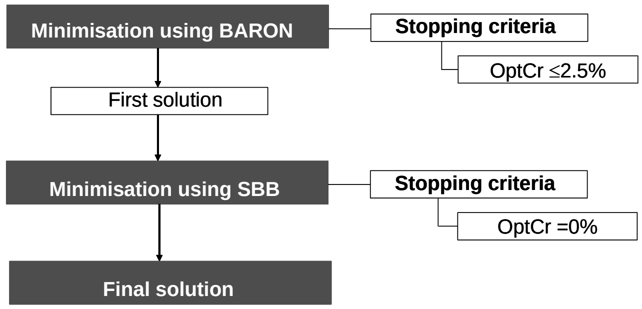

Figure 5.12- Computational approach to the optimisation process.

According to the above, the approach to the NLEPM will involve the following main stages:

(1) Minimisation of the CO_2 objective, using BARON and SBB solvers.

(2) Minimisation of the cost objective, using BARON and SBB solvers.

(3) Definition of CO_2 allowable levels between (1) and CO_2 values obtained with the minimisation of the cost objective (2).

(4) Minimisation of the cost objective constrained by the CO_2 allowable levels, using BARON and SBB solver.

(5) Construction of the final set of optimal solutions.

The GAMS code for the NLEPM solver may be found in Annex 10.

The process started again with the optimisation of each one of the objectives separately over the set of constrains. The final results of these individual optimisations are shown in table 5.12. The first solutions found with BARON solver are reported in Annex 11.

Table 5.12- Results of the single objective optimisation for the NLEPM.

	Absolute values		Unit values	
	Cost (M€)	CO_2 (Mton)	Cost (€/MWh)	CO_2 (ton/MWh)
Optimal cost solution (NLS0)	16621	310.8	31.537	0.590
Optimal CO_2 solution (NLS8)	23338	134.7	44.283	0.256

The elements in the first row indicate that the least costly solution (31.5 €/MWh) corresponds to an average value for the CO_2 emissions of 0.590 ton/MWh. The elements in the second row indicate that the least polluting solution (0.256 ton/MWh) corresponds to an average cost of about 44.3 €/MWh. This means that the least costly solution is 29% less expensive than the solution with the lowest emission levels. In addition, it should be noted that the corresponding emission levels are more than twice the ones obtained with the lowest CO_2 solution. Comparing these results to the ones obtained with the linear EPM, it is clear that reduction of the CO_2 emissions as a consequence of the wind power impact on the operating performance of the CCGT plants can only be achieved with increased economic effort. The NLEPM never reaches CO_2 emission levels as low as the EPM for the assumed electricity demand conditions, while the minimal CO_2 values are about 30% higher in the NLEPM than in the linear model.

As with the EPM, the process continued with the bi-objective optimisation, with each one of the objectives limited by the previously identified extreme values. Once more, optimisation BARON solver was used to solve the problem, with the relative optimal tolerance (Optcr) set equal to 2.5%. Hereafter the local solver SBB was called upon to work out the problem, imposing zero optimal tolerance. The process was repeated for each run conducted.

Table 5.13 presents the final data sets from this optimisation process. The elements in the second column represent the absolute optimal cost solution constrained by the CO_2 level indicated in the third column. The fourth and fifth columns represent the respective unit cost and CO_2 values. The last column present the run time for each simulation using SBB solver.

Table 5.13- Results of the two objective optimisation for the NLEPM.

Cost optimisation	**Absolute values**		**Unit values**		**Run time (min)**
	Cost (M€)	**CO_2 (Mton)**	**Cost (€/MWh)**	**CO_2 (ton/MWh)**	
NLS0	16621	311	31.537	0.590	2.9
NLS1	16882	275	32.033	0.522	8.1
NLS2	17149	250	32.539	0.474	7.5
NLS3	17392	225	33.001	0.427	8.3
NLS4	17722	200	33.627	0.379	7.2
NLS5	18111	175	34.365	0.332	7.4
NLS6	18640	150	35.369	0.285	7.5
NLS7	20319	138	38.554	0.262	1.8
NLS8	23338	135	44.283	0.256	0.02

All the models were formulated using GAMS and solved on a Intel Core Due, 987 MHz computer with 1GB memory. The first solutions found with BARON solver may be seen in Annex 11.

Figure 5.13 graphically represents the set of optimal solutions, corresponding to the average cost vs. CO_2 trade-off. The two extreme points of the line obtained correspond to the extreme solutions presented in Table 5.12.

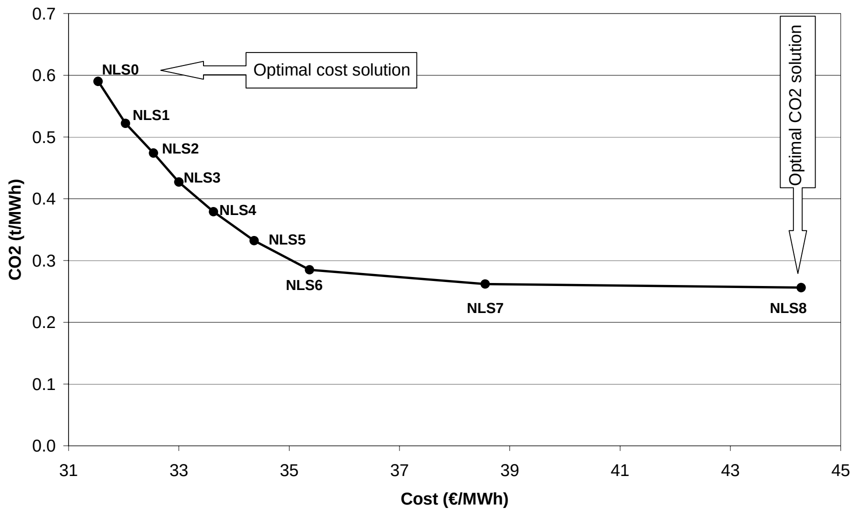

Figure 5.13- Pareto curve solutions for the NLEPM.

Table 5.14 describes the power generation expansion planning for these optimal solutions.

Table 5.14- Incremental installed power (MW) for the optimal solutions for the NLEPM.

		2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Total
	Coal	1950			300		750	450		750	300	4500
NLS0	Gas						330					330
	Wind			941	813	15	64		744	0	1271	3848
	Coal			300	900	300		1500	0	600	300	3900
NLS1	Gas	400	400									800
	Wind	1414		277		39	467		293	154	1769	4413
	Coal					300	1000	450		600	450	2800
NLS2	Gas	660	330	330	660						330	2310
	Wind	331	102	628	494	62	433		744	154	277	3225
	Coal									300	600	900
NLS3	Gas	660	330	330	660	330	990	400	330			4030
	Wind	320	107	697	431	74	335	135	23	827	634	3583
	Coal											
NLS4	Gas	400	400	330	730	330	1200	330	330	330	660	5040
	Wind	1414		146	517				141	543	464	3225
	Coal											
NLS5	Gas	400	400	400	800	330		1390		730	660	5110
	Wind	1414			54		598		771		388	3225
	Coal											
NLS6	Gas	2000	400		400	400	400	330	400	330	330	4990
	Wind	1118		349	255	144	16	183	329	425	431	3250
	Coal											
NLS7	Gas	3390		400	330	330	330	330	660	400	660	6830
	Wind	4569										4569
	Coal	0										
NLS8	Gas	3630	0	660	660	0	330	330	330	660	330	6930
	Wind	7500										7500

Table 5.15 presents the corresponding final configuration of the electricity system in 2017, described by the total installed power for each technology and by the respective contribution for electricity supply.

Table 5.15- Configuration of the electricity system in 2017 for the optimal solution.

		NLS0	NLS1	NLS2	NLS3	NLS4	NLS5	NLS6	NLS7	NLS8
Total installed power (MW)	Coal (new)	4500	3900	2800	900					
	Coal (existing)	1820	1820	1820	1820	1820	1820	1820	1820	1820
	Gas (new)	330	800	2310	4030	5040	5110	4990	6830	6930
	Gas (existing)	2916*	2916*	2916*	2916*	2916*	2916*	2916*	2916*	2916*
	Wind (new)	3848	4413	3225	3583	3225	3225	3250	4569	7500
	Wind (existing)	1515	1515	1515	1515	1515	1515	1515	1515	1515
	Large hydro	5805	5805	5805	5805	5805	5805	5805	5805	5805
	NWSRP[(1)]	3245	3245	3245	3245	3245	3245	3245	3245	3245
	Total	23979	24414	23636	23814	23566	23636	23541	26700	29731
Contribution to electricity supply (%)	Coal (new)	44	38	27	8	0	0	0	0	0
	Coal (existing)	13	15	11	18	10	0	0	0	0
	Gas (new)	3	5	21	33	49	49	48	59	51
	Gas (existing)	1	1	1	1	1	11	12	0	0
	Wind	14	16	13	14	13	13	13	16	24
	Large hydro	14	14	16	15	16	16	16	14	14
	NWSRP	11	11	11	11	11	11	11	11	11
	Total	100	100	100	100	100	100	100	100	100
Share of RES (%)[(2)]		39	40	39	39	39	39	39	40	49
External dependency (%) [(3)]		65	64	65	65	65	65	65	63	55
2017 electricity demand		85951 GWh								

*Includes 750 MW SCGT.
(1) NWSRP- Non wind special regime producers. Includes the production from cogeneration and renewable sources except wind and large hydro.
(2) Share of electricity consumption from RES. Large and small hydro power share corrected by the HPI (equal to 1.22) of the base year of Directive 2001/77/EC (1997).
(3) Proportion of energy used in meeting the demand for electricity that comes from imports.

From these results it can be concluded that the least costly solution assumes investments mainly in new coal power plants. New wind power appears only after 2010 due to the renewable constraint. According to this solution, in 2017:

- The electricity supply would come mainly from new and old coal power plants.
- CCGT would also be operating but representing only about 4% of the electricity supply.
- The remaining electricity would come from non large thermal power stations namely, wind power (about 14%), large hydro (about 14%) and NWSRP (about 11%).
- The electricity consumption from renewable energy sources would represent 39 %

of the total electricity demand (meeting but not exceeding the renewable Directive).

- About 65% of the electricity consumption would come from imported primary energy sources (mainly coal).

- The results are not much different from the ones obtained with the EPM. Both the costs and CO_2 values are close to the ones obtained with the linear model and so are the proposed investment strategies.

The lowest CO_2 emission solution represents a completely different scenario. It assumes the complete disinvestment in coal, and a significant investment in CCGT and renewable energy sources, maximising the use of wind. According to this solution, in 2017:

- The electricity supply would come mainly from new gas power plants.

- Old coal power plants would not operate and no new coal plants would be added to the system.

- The remaining electricity would come from non large thermal power stations namely, wind power (about 24%), large hydro (about 14%) and NWSRP (about 11%).

- The electricity consumption from renewable energy sources would represent 49% of the total consumption (outreaching the renewable Directive).

- About 55% of the electricity consumption would come from imported primary energy sources (natural gas).

- In spite of the estimated wind power impact on the CCGT operating performance, the investment strategy is also close to the one obtained with the EPM. In fact, the minimisation of CO_2 emissions may only be achieved by the maximisation of electricity generation from wind power combined with clean thermal power plants like CCGT.

- The costs and CO_2 values are now higher than the ones obtained with the linear model. The integration into the model of the estimated impact of wind power in CCGT operating performance resulted in almost 14% cost increase and also in a 30% CO_2 emissions increase in comparison with the EPM results.

The initial effect of imposing increasing CO_2 constraints on the model is a reduction of the investment in new coal power plants, combined with the increase of investment in new onshore wind power plants and a small increase of investment in new CCGT. For solution NLS1, the least costly way to achieve the imposed CO_2 levels is still relying mainly on coal power production but investments in new wind power plants are required in order to offset the CO_2 emissions.

Solutions NLS2 and NLS3 present both a reduction on installed coal and wind power comparatively to NLS1. The integration of new CCGT into the system compensates this reduction and ensures the imposed CO_2 limits. Solution NLS4 proposes no more investments on new coal but electricity generation from existing coal power plants still represents 10% of the total electricity supplied. Solutions NLS5 and NL6 represent already highly environmentally constrained solutions. Both these solutions present close strategies, where the reduction of the CO_2 levels is mainly achieved by the full replacement of the coal power production by the natural gas power production. The installed wind power will only present a more significant increase when very low CO_2 limits are imposed to the model, as in solution NLS7.

For solutions NLS2-NLS6, the share of electricity generated for RES is equal to 39%, a value just enough to meet the minimal goal imposed by renewable Directive 2001/77/EC for Portugal. Solutions NLS1 and NLS7 surpass this minimal request, due to their higher total installed wind power. The level of wind power in the system also strongly influences the value of the external dependency, assigned to each solution. The results of the NLEPM indicate that solutions NLS1 and NLS7 not only present higher RES share but also contribute to the reduction of the external energy dependency.

It should however be underlined that the optimisation procedure aims to reduce a very large number of possible plans, to a small number of plans that are to be presented to the decision makers. Due to the uncertainties associated with the calculations it may not be easy to discard some possible plan that although not being optimal is not significantly worse than another mathematical optimal plan (Hobbs and Meier, 2003). As seen, cost and CO_2 tradeoff analysis leave aside important aspects like the external dependency or the need to diversify the fuel mix of the country. It is worth then to analyse some other solutions that are not located in the Pareto front but may bring some additional advantages to the system with out seriously compromising cost or CO_2 objectives.

V.6.3.1 Non optimal solutions of NLEPM

For obtaining non optimal example solutions for the model, sensitivity runs for solutions NLS3, NLS4 and NLS5 were conducted. For this it was assumed that additional constraints were added to the model, imposing minimum predefined installed wind power levels for the future. The model was run again and new solutions were obtained, corresponding to the same CO_2 level but with higher costs and consequently moving away from the original Pareto front.

As an example, it was assumed that the decision maker adds an additional constraint, imposing that the new installed wind power in 2012 must reach at least 6500 MW, as indicated in equation 5.52.

$$IP_{3a,2012} \geq 6500 \qquad (5.52)$$

Table 5.16 summarises the results of this sensitivity exercise for three examples (NLS3, NLS4 and NLS5). The final configuration of the electricity system in 2017 along with expected average cost and CO_2 emissions, for the original Pareto solutions and for the ones obtained after imposing additional constraints to the model are presented.

The results indicate that imposing values for installed wind power beyond the original optimal solutions would affect the operating conditions of the system and the share of electricity supplied by each technology. In general, the electricity production from CCGT would be reduced but the share of electricity produced from both coal and wind power would increase. This new impositions lead to higher costs but, at the same time, contribute to the reduction of the external dependency and to the increase of the share of electricity produced from RES.

Table 5.16- Results for the original Pareto and additionally constrained solutions in 2017

		NLS3	NLS3.1	NLS4	NLS4.1	NLS5	NLS5.1
Observations		Pareto	$IP_{3a,2012} \geq 6500$	Pareto	$IP_{3a,2012} \geq 6500$	Pareto	$IP_{3a,2012} \geq 6700$
Total installed power (MW)	Coal (new)	900	2700		2400		600
	Coal (existing)	1820	1820	1820	1820	1820	1820
	Natural gas (new)	4030	1650	5040	1860	5110	3720
	Natural gas (existing)	2916*	2916*	2916	2916*	2916*	2916*
	Wind (new)	3583	6500	3225	6514	3225	6500
	Wind (existing)	1515	1515	1515	1515	1515	1515
	Large hydro	5805	5805	5805	5805	5805	5805
	NWSRP	3245	3245	3245	3245	3245	3245
	Total	23814	26151	23566	26075	23636	26121
Contribution to electricity supply (%)	Coal (new)	8	26	0	23	0	5
	Coal (existing)	18	5	10	11	0	7
	Natural gas (new)	33	16	49	18	49	36
	Natural gas (existing)	1	6	1	2	11	4
	Wind	14	22	13	22	13	22
	Large hydro	15	14	16	13	16	15
	NWSRP	11	11	11	11	11	11
	Total	100	100	100	100	100	100
Share of RES (%)		39	46	39	45	39	46
External dependency (%)		65	57	65	58	65	57
Cost (€/MWh)		33.001	33.864	33.627	34.961	34.365	36.950
CO_2 (ton/MWh)		0.427	0.427	0.379	0.379	0.332	0.332
2017 electricity demand		85951					

*Includes 750 MW SCGT.

(1) NWSRP- Non wind special regime producers. Includes the production from cogeneration and renewable sources except wind and large hydro.

(2) Share of electricity consumption from RES. Large and small hydro power share corrected by the HPI (equal to 1.22) of the base year of Directive 2001/77/EC (1997).

(3) Proportion of energy used in meeting the demand for electricity that comes from imports.

For example solution NLS4.1 is 4% more expensive than the original NLS4. However, in 2017 it would be possible to reduce the external dependency of the electricity generation sector by 7% and the share of RES would increase by 6%, comparatively to the original values reported under NLS4. Concerning the coal/natural gas balance, NL4.1 represents also a more equilibrated solution, allowing for the diversification of suppliers of primary energy thereby increasing the security of supply.

Figure 5.14 graphically represents the set of the original compromise Pareto solutions for the NLEPM and the new solutions that, although representing trade-offs between the two objectives, do not belong to the Pareto front of the original NLEPM.

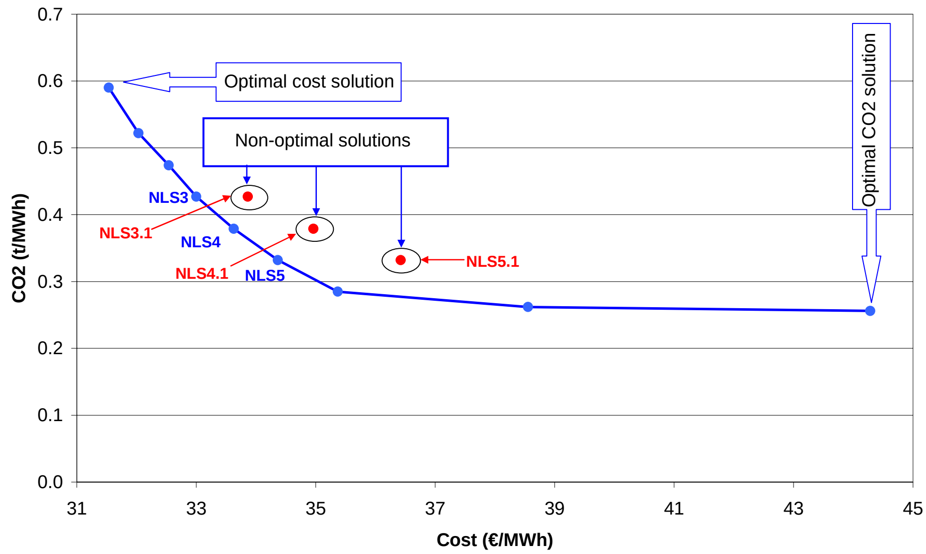

Figure 5.14- Original Pareto solutions and additionally constrained solutions.

The aim of this exercise was not to present an exhaustive description of all possible plans, but rather draw attention to some examples demonstrating the relevance of presenting other possible strategies that, although not being original Pareto solutions, may be interesting from the decision maker's perspective. The three non optimal solutions analysed ensure the required minimum CO_2 levels, set for each run, and present also a cost increase of less than 10% over the optimum solutions. However, they may become more interesting when other aspects, like the external energy dependency or the need to balance coal and gas in the system, are considered.

V.6.3.2 Final comments

The results obtained, and in particular the curve presented in Figure 5.13, indicate that the drop of CO_2 emissions per unit of cost falls deeply for highly environmentally constrained solutions. Between the optimal cost solution and NLS6 the cost per ton of CO_2 reduction is 12.6 €. A value obtained mainly due to the high environmental gains achieved with the substitution of coal power electricity generation by wind and CCGT production. Between NLS6 and optimal CO_2 solution, the $\frac{\Delta CO_2}{\Delta cost}$ ratio increases to 307.4 €/ton CO_2. For this range of the curve, the more pollutant plants are not producing any electricity any more and the environmental gains may only be achieved by the installation of new CCGT and new wind power plants.

The results may be described by four main scenarios:

- **Scenarios with low CO_2 restrictions** (NLS1). The cost minimisation with minimal environmental restrictions is achieved by the combined investment in new coal and wind power plants. The electricity production comes mainly from existing and new coal power plants. The onshore wind power production allows for higher electricity generation from RES and the system exceeds the minimum requirements set by Directive 2001/77/EC for Portugal Also, this wind power scenario allows for slightly reducing the external energy dependency to 64%.

- **Scenarios with moderate CO_2 restrictions** (NL2, NLS3). Investments in new coal power plants decline but, on the other hand, investments in new CCGT increase. However electricity production from coal power plants still represents an important share of the total electricity supplied. There are also new investments in wind power plants, although less significant than in NLS1. In 2017, the electricity consumption from renewable energy sources represents 39% of the total electricity demand and the share of electricity consumption from imported primary energy sources is about 65%.

- **Scenarios with strong CO_2 restrictions** (NLS4-NL6). The less expensive way to ensure severe CO_2 limitation is the strong investment in new CCGT with electricity production coming mainly from the new and existing natural gas power plants. The investment in new wind power plants is slightly lower than in previous solutions. In 2017, the electricity consumption from renewable energy sources represents 39% of the total demand and, the share of electricity consumption obtained from imported primary energy sources is about 65%. By limiting the total wind power production, the model attempts to minimise the effects on CCGT operating performance. Under these solutions, the thermal power mix relies mainly on natural gas which reduces the possibility of diversification of primary energy suppliers and makes the electricity system highly vulnerable to the international prices of natural gas.

- **Scenarios with extreme CO_2 restrictions** (NLS7). This extreme condition may only be achieved by the replacement of the existing CCGT plants by new CCGT and new wind power plants. In 2017, the share of renewable energy coming from renewable energy sources is more than 40% and the electricity consumption coming from imported primary energy sources declines to about 63%. As with solution NLS6, the issues of security of supply and exposure to international natural gas price fluctuations are important aspects to consider under this solution.

Power system planning is not an exact science and the robustness of the results across alternative scenarios must be checked. This was done by a sensitivity analysis, where important parameters of the model were changed and new results were generated. The next section of this chapter presents the results of this analysis.

V. 6.4 Sensitivity analysis

The increasing uncertainty surrounding the electricity generating sector makes the sensitivity analysis an essential toll to long term planning. The fuel price volatility and the emissions trading schemes, probably represent the major sources of uncertainty, since the economic interest of wind power largely depends on these two factors. In this section, both these aspects will be analysed. Preliminary investigations on the evolution of the fuel prices and of the CO_2 allowances prices were conducted and some possible future scenarios were drawn. Whereafter the optimisation was conducted with the NLEPM. Sensitivity analysis in relation to the discount rate was also carried out, following IEA/NEA (2005) scenarios.

The sensitivity analysis will focus on two main scenarios: the optimal cost solution, without environmental restrictions (solution Opt. cost) and the Kyoto reference solution as described in Section V.5.1, with an average CO_2 maximum emission limit equal to 20 Mton/year for the planning period (solution SR1). Additional scenarios were also considered in some of the sensitivity runs to better illustrate the results of this exercise.

V.6.4.1 Fuel Price

Both the EPM and the NLEPM assume that coal and natural gas prices will remain stable and at 2005 levels during the 10 years planning period. However, between 1999 and 2005 the fuel prices followed an increasing pattern, as may be observed from Figure 5.15.

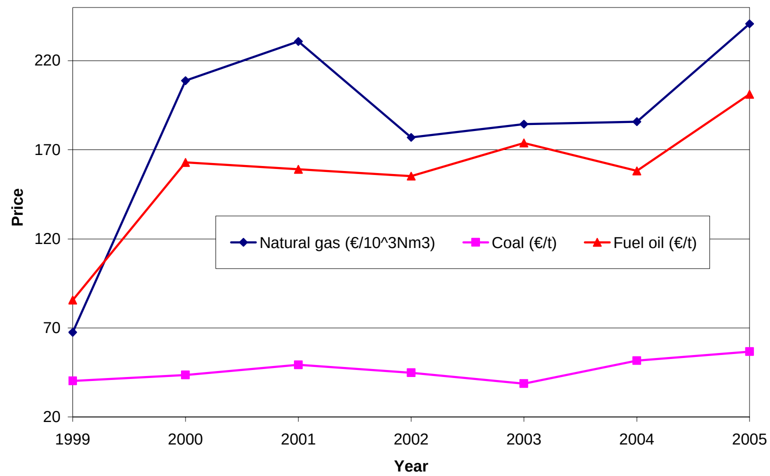

Figure 5.15 – Average price of fuel purchased by EDP producers (2005 values). Source: EDP (2006b), EDP (2004a), EDP (2002).

The household and industrial consumers' prices seem to indicate that the natural gas prices are giving signs of stabilisation in 2006 and beginning of 2007, after the high increase in the first semester of 2005. The European Commission projections (European Commission, 2006a) indicate that an average annual growth rate of more than 7% may be expected for gas, between 2000 and 2010. Between 2010 and 2020, this growth rate may be close to 0.9%. For the sensitivity analysis two possible annual average growth rates for natural gas were analysed: moderate growth rate (4% per year) and high growth rate (7% per year). Table 5.17 summarises the main results of the sensitivity run for the NLEPM.

According to the results, the natural gas price increase would lead to a stronger investment in coal power plants and a reduction of gas fired electricity generation. The optimal cost solution indicates that the wind power capacity remains close to the base scenario, for both the moderate and high gas increase sensitivity run. In 2017, electricity production would come mainly from existing and new coal power plants.

For the Kyoto reference scenario (SR1), the model converges to solutions characterised by strong investments in new coal power plants combined with high installed wind power capacity (both on and offshore). For the last years of the planning period, natural gas would become too expensive to compete with coal or wind power electricity production and the electricity production from CCGT would be kept at minimal levels set by equation 5.25.

Table 5.17- Results of the natural gas price sensitivity run for the NLEPM in 2017.

		Moderate gas price growth rate (4%)		**High gas price growth rate (7%)**	
		Opt. cost	**SR1**	**Opt. cost**	**SR1**
Total installed power (MW)	Coal (new)	4800	4300	4800	4500
	Coal (existing)	1820	1821	1820	1821
	Natural gas (new)		2190	330	1790
	Natural gas (existing)	2916	2916	2916	2916
	Wind (new)	4102	7034	4102	7500
	Wind (existing)	1515	1515	1515	1515
	Large hydro	5805	5805	5805	5805
	NWSRP	3245	3245	3245	3245
	Total	24203	28826	24533	29092
Contribution to electricity supply (%)	Coal (new)	47	40	47	41
	Coal (existing)	10	9	10	6
	Natural gas (new)	0	3	3	3
	Natural gas (existing)	3	0	0	0
	Wind	15	23	15	24
	Large hydro	14	14	14	15
	NWSRP	11	11	11	11
	Total	100	100	100	100
Cost (M€)		16878	19502	17069	20223
CO_2 (Mton)		316	200	316	200
Cost (€/MWh)		32.026	37.005	32.387	38.373
CO_2 (ton/MWh)		0.600	0.379	0.600	0.379
2017 electricity demand		85951 GWh			

According to the results, the rising trend of the natural gas price may result in a different optimal configuration of the electricity system. Even when imposing emission limits, coal will have an important role in particular in the later years of the planning period. According to solution SR1, the minimum Kyoto commitments would be achieved mainly by combining coal power electricity production (especially from new plants) and wind power generation. For this solution, the average yearly cost increase comparatively to the base case scenario is close to 3.4 €/MWh for the low gas price growth rate simulation and 4.7 €/MWh for the high gas price growth rate simulation.

However, it is also important to analyse the simultaneous increase of both natural gas and coal prices. According to the European Commission projections, coal price will also increase by about 4% per year between 2000 and 2010 and by about 1.2% per year between 2000 and 2010. Table 5.18 summarises the main results of the sensitivity run combining an annual growth rate of 4% for natural gas with an annual growth rate 2.6% for coal.

Table 5.18- Results of the natural gas and coal prices sensitivity run for the NLEPM in 2017.

		Moderate coal and gas prices growth rate	
		Opt. cost	SR1
Total installed power (MW)	Coal (new)	4800	4200
	Coal (existing)	1820	1821
	Natural gas (new)		2190
	Natural gas (existing)	2916	2916
	Wind (new)	4096	7500
	Wind (existing)	1515	1515
	Large hydro	5805	5805
	NWSRP	3245	3245
	Total	24197	29192
Contribution to electricity supply (%)	Coal (new)	46	39
	Coal (existing)	11	8
	Natural gas (new)	0	4
	Natural gas (existing)	3	0
	Wind	15	24
	Large hydro	14	14
	NWSRP	11	11
	Total	100	100
Cost (M€)		17725	19970
CO_2 (Mton)		316	200
Cost (€/MWh)		33.633	37.892
CO_2 (ton/MWh)		0.599	0.379
2017 electricity demand		85951 GWh	

The results are not much different from the previous runs testing natural gas price increases individually. Electricity production from coal power plants would still represent an important share of the total electricity production in 2017, even for scenarios with environmental restrictions. In the same way, the least costly solution for the Kyoto reference scenario points to the maximisation of the wind power electricity generation combined with a high share of electricity from existing and new coal power plants. These results are dependent on the cost structure of the analysed technologies and reflect the high sensitivity of CCGT to fuel price changes and the less sensitivity of coal power plants to changes in variable costs.

V.6.4.2 Discount rate

For base case of the NLEPM a 5% discount rate was used. ERSE (2005) computed the cost of capital of the regulated companies and proposes real values between 4.1 and 6.2% for the electricity distribution companies and 2-3.8% for the electricity transmission companies. No information is available for the generation sector, but assuming a higher risk of this business a higher cost of capital may also be expected. Following the IEA/NEA (2005) methodology to analyse the costs of electricity generation, the sensitivity analysis will now address the impact of raising this value to 10%. Table 5.19 summarises the main results of this sensitivity run for the NLEPM.

Table 5.19- Results of the discount rate sensitivity run for the NLEPM in 2017.

		10% discount rate		
		Opt. cost	SR1	SR2[1]
Total installed power (MW)	Coal (new)	4200		3750
	Coal (existing)	1820	1821	1822
	Gas (new)	660	5040	1200
	Gas (existing)	2916	2916	2917
	Wind (new)	3960	3238	3586
	Wind (existing)	1515	1515	1515
	Large hydro	5805	5805	5805
	NWSRP	3245	3245	3245
	Total	24121	23580	23840
Contribution to electricity supply (%)	Coal (new)	41	0	36
	Coal (existing)	14	0	16
	Gas (new)	4	49	7
	Gas (existing)	1	11	1
	Wind	15	13	14
	Large hydro	14	16	15
	NWSRP	11	11	11
	Total	100	100	100
Cost (M€)		14039	14435	14056
CO_2 (Mton)		299	200	275
Cost (€/MWh)		26.639	27.391	26.671
CO_2 (ton/MWh)		0.568	0.379	0.522
2017 electricity demand			85951 GWh	

[1] CO_2 maximum emissions limit equal to 275 Mton for the planning period.

Theoretically, increasing the discount rate favours the technologies with low investment costs and higher variable costs (O&M, fuel and CO_2 allowances). The optimal cost solution with out environmental constraints still points to high investments on coal power plants, but additional CCGT are already included in the electricity system due to their low investment costs. For the Kyoto reference solution (SR1), the results are also not much different from the ones for the base scenario. The share of the coal power production is null in 2017 because, due to the higher discount rate, in the long run electricity production from CCGT becomes economically more interesting and avoids CO_2 emissions from coal power plants. For both these runs, the effect on installed wind power is largely levelled out by the renewable constraint of the model.

For low environmental restrictions (solution SR2), the higher discount rate leads to a mix of technologies different from Solution NLS1, presented in Table 5.15. For this sensitivity run, new CCGT investments partially replace the technologies with high initial investment costs, reducing both coal and wind power investments. For this run, the negative effect of increasing discount rates is notorious not only for coal power plants but also for new wind investments.

According to the results, increasing the discount rate favours the CCGT and increases the proposed investments in this technology. The results of the sensitivity analysis follow the expected pattern, with high investment cost technologies (coal and wind power) being displaced by a lower investment cost technology (gas power). Opposite to the conclusions for the fuel price simulations, the discount rate considerably affects those plants with greater investment cost. Coal power plants are more sensitive to the choice of the discount rate than CCGT plants, losing there some of their financial advantage.

V.6.4.3 Emission cost

Both the EPM and the NLEPM assume that the price of EU allowances (CO_2 emission cost) would remain stable and close to the beginning of 2006 levels. However, the volatility of the market is high and since the second quarter of 2006 we have been witnessing a general decrease of these prices. Some analysts interpret this trend as the response of the market to the compliance reports published by several EU members in May 2006. The spot prices reached values lower than 1 €/tonCO_2, but the futures market still trade allowances at prices between 14 and 17 €/ tonCO_2. The analysts expect an average price between 20 and 30€/ ton CO_2 for the 2008-2012, but warn about the immaturity of the market and on the difficulty to make long term projections[82]. The EU projections for electricity generating costs in 2030 also assume 20 -30 €/ton CO_2 (Commission of the European Communities, 2007a).

Figure 5.16 represents the average price of the traded CO_2 certificates, where the price decline after May 2006 is evident.

Taking into consideration this downward trend, two possible scenarios for the CO_2 emission cost were considered for the sensitivity analysis: the moderate price scenario (10 €/t CO_2) and the zero price scenario (0 €/t CO_2). This last scenario will give a picture of what would be the optimal electric system with environmental constraints but without any financial penalties imposed to CO_2 emitters.

[82] EU allowances market analysis obtained from energy consultants: http://www.co2prices.eu/), http://www.emissierechten.nl/co2prices/ and http://www.icfi.com/Newsroom/eua-prices-2006.asp (all drawn in March 2007)

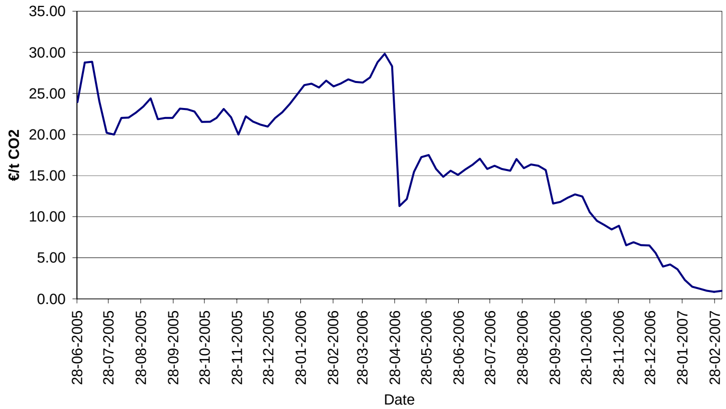

Figure 5.16 – Average price of traded CO_2 certificates. Source: EXAA site.

Table 5.20 summarises the main results of the sensitivity runs for the NLEPM.

Table 5.20- Results of the CO_2 emission cost sensitive run for the NLEPM in 2017.

		Zero CO_2 price (0 €/ton)		**Moderate CO_2 price (10 €/ton)**	
		Opt. cost	**SR1**	**Opt. cost**	**SR1**
Total installed power (MW)	Coal (new)	4900		4600	0
	Coal (existing)	1820	1821	1820	1821
	Gas (new)		4950	400	5040
	Gas (existing)	2916	2916	2916	2916
	Wind (new)	3678	3326	3811	3225
	Wind (existing)	1515	1515	1515	1515
	Large hydro	5805	5805	5805	5805
	NWSRP	3245	3245	3245	3245
	Total	23879	23578	24112	23567
Contribution to electricity supply (%)	Coal (new)	47	0	45	0
	Coal (existing)	10	0	12	1
	Gas (new)	0	48	3	48
	Gas (existing)	3	13	1	11
	Wind	14	13	14	13
	Large hydro	15	15	14	16
	NWSRP	11	11	11	11
	Total	100	100	100	100
Cost (M€)		11364	14315	13769	15865
CO_2 (Mton)		316	200	316	200
Cost (€/MWh)		21.563	27.162	26.127	30.104
CO_2 (ton/MWh)		0.600	0.379	0.600	0.379
2017 electricity demand			85951 GWh		

For the optimal cost solution, in respect for the share of each electricity generation technology, the CO_2 price reduction does not seem to affect the results significantly even when a zero value is assigned to the emissions. The reduction of the CO_2 prices reinforces the position of coal as the least expensive electricity generation plants. For environmentally constrained solutions, gas fired production maintains a dominant role. For solution SR1, CCGT electricity production represents about 59% of electricity demand for the moderate CO_2 price scenario and 61% of electricity demand for the zero CO_2 price scenario.

The reduction of CO_2 price will favour CCGT in particular. The average generation costs of coal power plants would also be reduced for these scenarios, but it seems that the combination of CCGT with wind power becomes economically more interesting. This way, although wind power affects CCGT performance, the reduction of the CO_2 prices brings economic advantages to both existing and new CCGT allowing to increase their electricity production even in the presence of large wind power scenarios.

In general, the reduction of the CO_2 price would lead to a reduction of the average electricity cost. For the Kyoto reference scenario the electricity cost would decline by 3.5 €/MWh for the moderate CO_2 price sensitivity simulation and by 6.4 €/MWh for the zero CO_2 price sensitivity simulation.

V.7. Discussion of the results

The development of the NLEPM implied the assessment of the impacts that large wind power scenarios may have on the Portuguese thermal power system efficiency. The quantification of these impacts was based mainly on the results of the simulation of the Portuguese system under different wind power scenarios in 2016 and on the empirical data characterising the operating conditions of a CCGT power plant.

From the obtained exploration planning, it was possible to conclude that the increase of the installed wind power would mainly affect CCGT operation. With the exception of the high growth scenario, where a reduction on the number of operating hours for older coal groups could be expected, coal power production would remain stable with these plants operating near full load. The SCGT are minimally affected, because they work mainly as operational reserve and their load level remains very low for every wind power scenario.

For the CCGT, increasing wind power scenarios affects both the number of operating hours and the average load level of these thermal power plants. This leads to a growing inefficiency of these plants, consequently increasing specific gas consumption and specific CO_2 emission factors, and may put in question the value of using wind power to reduce operating costs and to control emissions. However, the results indicate that in spite of this efficiency loss, both the CO_2 abatement and value of wind power still increase with the increasing wind power in the Portuguese system.

These results are explained partially by the expected particular configuration of the Portuguese electricity system in 2016, characterised by a large share of hydro power, no nuclear power plants and the possibility of exchanges with Spain. The incremental wind power replaces mainly CCGT power and only for high growth wind scenarios there would be an important effect on the coal power production. However, adding wind power to the system will increase exports and, as so, the expected reduction of the thermal power production for large wind scenarios may be offset by the possibility of transmission. The analysis assumes a fixed non wind capacity in the system, meaning that increasing wind power will increase the total installed power. Additionally, the evolution of installed wind power in Spain is not modelled and present market conditions are assumed. This results in increased capacity of production in Portugal and may explain the large increase in net exports. This way, the possibility of exchanges smoothes out the variations and the efficiency of CCGT might not be as affected as it would be in the no transmission case.

Studies for other countries, like Denmark, Ireland and Germany indicate larger CO_2 abatement potential, but lower values for the value of wind. However, most of these studies assume that large amounts of wind added to the system will mainly replace coal and to a lesser extent gas. Holttinen and Tuhaken (2004) highlighted this issue, underlining that if gas becomes very expensive, the operating cost of gas plants will rise which will result in wind power replacing gas instead of coal, as observed in the Portuguese case. This results in lower environmental gains but is more cost effective. It is also important to point out that the Portuguese analysis, already takes into account the CO_2 emissions cost.

The importance of the hydro power sector in Portugal, might lead to the assumption that the impact of wind power on thermal system costs would not be significant. However, from the results it seems clear that although hydropower plays an important role in the management of the possible wind power fluctuations in Portugal, it will not avoid important consequences on the thermal power plants performance. In fact, about half of the total Portuguese hydro power capacity is of run of river type with little or no storage capacity, presenting this way a low ability to backup fluctuations of the electricity supply or demand.

The run was made for one year, with weekly time steps subdivided in four “hourly steps” and assuming a weekly average load factor of the wind power plants. This allows to obtain the average output of each power plant for each one these “hourly steps”, but the effect of wind power fluctuations during a day is lost. It was however possible to estimate the effect of seasonal changes on both the wind and hydro sectors. Holttinen and Tuhkanen (2004) used also weekly time steps for the analysis of the running/dispatch of the Nordic electricity system for a fixed year. However, Rosen et al. (2007), deal already with the intradaily problem by presenting a newly developed tool that allows long range planning based on a hourly load curve and on hourly mean values for the cumulative wind power feed-in. For the Portuguese case, the daily fluctuations of the wind power may be mainly compensated by SCGT and hydro power. As so, it is assumed that the power output of the CCGT and coal power plants will remain close to the average “hourly steps” values obtained.

According to the 2016 planning, about 21%[83] of wind power penetration may be achieved in Portugal but with some losses of efficiency of the global system. The estimated value of wind is about 36.5 €/MWh and the CO_2 abatement of wind may reach values close to 0.276 tonCO_2/MWh. The average variable cost of the system for the high wind growth scenario is about 27% lower than for the low wind growth scenario. As for the CO_2 average emissions, a 15% reduction may be expected for the high growth wind scenario over the low growth wind scenario.

The values presented so far result from a fixed analysis of the system, obtained from the exploration planning based on minimisation of the variable cost. From these results, a function relating large scale wind production and average operating characteristics of the CCGT system was estimated. This function was generalised for the planning period and introduced in the model in an attempt to derive optimal generating strategies for a 10 year period, taking into consideration the interdependency of the power plants operation and leading to the NLEPM.

The results of the NLEPM are not directly comparable with the ones reported by the 2016

[83] Corresponding to high wind growth scenario (W4) and assuming an average load factor of 26%.

exploration planning. Firstly, the 10 year NLEPM aims to optimise the total cost of the system including the variable and capital costs. While the 2016 analysis assumes certain scenarios and optimises the operating schedule of the plants in the system (short-run planning), the NLEPM aims to define the best scenarios describing the mix of the system and the optimal scheduling (long-term planning). Another important aspect is that the NLEPM doe not take into consideration the possibility of imports or exports for the optimisation process and aims to find optimal electricity plans to meet internal demand.

The NLEPM and the EPM, generate rather consistent results. However, there are some important differences in particular in what concerns the role of wind power in the system. In the linear model, wind power presents a clear competitive advantage over CCGT, contributing to both lower costs and emission reductions. As for the NLEPM, increasing wind shares in the system affect the performance of CCGT plants. For scenarios with high shares of gas fired units, wind power investments are kept at lower levels although always ensuring the minimal RES requirements. The combination of CCGT and strong wind power investments will only be optimal for highly environmentally constrained scenarios. These results are mainly due to the underlining assumption that coal power performance would remain largely unaffected by increasing wind shares.

Using the NLEPM also results in higher cost values. For example, the cost of NLS4 (Kyoto reference solution) is about 1.1% higher than S4, assuming similar CO_2 levels and this difference increases for solutions with higher shares of electricity generation from gas fired units. It also becomes clear that high environmental constraints do not necessarily lead to high wind power solutions. In fact the results presented in Table 5.16 indicate that for the Kyoto reference solution, high wind power scenarios could increase total cost by about 4% while maintaining the same CO_2 values. This average cost increase represents a little less than 1% of the present electricity price paid by the average domestic consumer[84] and contributes to a reduction of about 7% on primary energy imports for electricity production. This exercise suggests that it is possible to increase wind power shares beyond the optimal costs, with some negative consequences on cost but with important gains in what concerns external energy dependency and security of supply.

The NLEPM demonstrates that computing the emissions reduction and the operating cost

[84] January 2006 values: 14 cent/kWh.

increase from wind power using a linear model represents a simplification of the reality. Onshore wind power remains fundamental to meet the renewable and Kyoto goals, but the economic advantage of wind over the CCGT detected in EPM is now partly offset. However, the sensitivity analysis demonstrated that natural gas price increase is particularly relevant for the decision process and if the European Commission (2006a) projections become effective, the combination of coal with large wind power scenarios may become the economically more interesting option even for environmentally constrained scenarios.

In fact, the sensitivity analysis indicates that the results strongly depend on highly volatile elements, being particularly sensitive to natural gas price forecasts. The cost of the CCGT plants depends mainly on their operational costs while for coal power plants the investment cost is much more relevant than the operational costs. This makes CCGT much more sensitive to variations on the variable costs (fuel and CO_2) and coal power plants much more sensitive to variations on the discount rate. The effect of these sensitivity simulations on installed wind power, although visible, is in large extent levelled out by the minimal RES requirements.

V.8 Conclusions

This study addressed the electricity planning in Portugal using two different models that differed mainly on the assessment of the impact of wind power on the thermal power system operation. The models aimed to establish an investment and generation plan for the electricity system, minimising costs and CO_2 emissions during the next 10 years. The formulation of the models involved extensive data collection from official reports and information published by the system manager. Some of this information is even considered confidential and special care had to be taken for its inclusion in the models. It was also necessary to proceed with the translation of legal and system constraints into mathematical relationships, in order to adapt the model to the Portuguese conditions. For the NLEPM additional data was obtained with the REN collaboration on the process.

According to the results, the increasing penetration of wind power in the system will have significant effects on the CCGT operation and on the theoretically expected cost reduction and environmental gains. However, opposite to other European studies, the results indicate that the value of wind power and its CO_2 abatement potential still present an increasing trend, partially due to the possibility of exports and to the particular configuration of the Portuguese electricity system.

As wind power capacity increases, the extra cost of part load operation of CCGT leads to an increase of their global operating costs. Due to this, the model penalises the combination of wind and CCGT, favouring the coal-wind power mix in order to minimise costs. Nervertheless, the model results indicate that under the assumed conditions, the least expensive way to achieve the Kyoto protocol reference solution (average $CO_2 \leq 20$ Mton/year for the 2008-2017 period) is the strong investment in new CCGT and the continuous investment in new wind power plants during the planning period.

The results indicate that for low CO_2 levels (strongly environmentally constrained model), the cost minimisation should involve large CCGT investments and not necessarily maximise wind power in the system. However, solutions with higher wind penetration, although not optimal from the cost minimisation point of view, might reduce external energy dependency with the country's security of supply, compensating for the cost increase. It seems then, that exclusively relying on the cost aspect for decision making may be a vision too simplistic for such a complex problem.

Long range energy planning involves forecasting parameters like fuel and CO_2 prices, which is not an easy and straightforward task. The energy market is extremely volatile and highly sensitive to external problems, politics, government regulation and technological developments. Although the recent decrease of the CO_2 prices might be seen as a sign that it will be possible to meet the Kyoto objectives without a high financial effort, the futures market of CO_2 still points towards higher prices for the next years. The natural gas prices increased greatly in 2005 and although some signs of stabilisation are felt in the market, the prices are still rising. In addition, in March 2007, the European Commission agreed on the objective to meet 20% of their energy needs with renewables and increase the emissions cut objective, and set a firm target of cutting 20% of the EU's greenhouse gas emissions by 2020[85].

[85] http://ec.europa.eu/energy/energy_policy/index_en.htm

As Hobbs (1995) states “no one resource plan will be the best under all possible futures”. The sensitivity analysis showed that the planning process is very responsive to variations on the parameters, and the recent developments of the market clearly demonstrate that a 10 year period involves a lot of uncertainty: the relationship between fuel prices may change, the CO_2 prices may contribute to this change or become a major cost source and the legal environment will certainly suffer modifications. However, it seems obvious that the trend in the EU is towards increasing the RES share. Wind power has the clear advantage of having operational costs invulnerable to fuel and emisisons market volatility. In fact, the only certain element of the planning model is that, regardless of politics and of the market behaviour, in 10 years wind will still be blowing for free.

Wind power has as a fundamental role on meeting the renewable and Kyoto protocol’s commitments. For all the scenarios analysed and regardless of the sensitivity simulations performed, installed wind power must reach at least 4740 MW in 2017 and careful management of the hydro sector must be ensured. For most of the solutions, total installed wind power converges to values close to 5000 MW or even higher. Portugal has the possibility of extensively using the hydro sector for the management of large wind power levels in the system and, the planning studies of the Portuguese generating system, concluded that the use of hydro schemes with reversible capacities to ensure the adequate levels of security of supply is the most appropriate solution. Therefore, it is fundamental to proceed with the planned hydro schemes in order to avoid possible situations of operational reserve deficit (Esteves et al., 2003). At the same time, these hydro schemes represent an important contribution to meet the RES goals established for Portugal (Ferreira et al., 2007a). Hydro power production can actively contribute to reduce the effect of wind power on thermal power operation, but as the results demonstrate these effects are still significant and should not be disregarded in the electricity planning process.

A previous study (Saleiro et al., 2007) analysed the cost of the electricity generation options, based on private and external costs of generation in Portugal. The study concluded that the financial cost of wind power is still higher than the CCGT, but when the external costs are considered the results change and the CCGT reaches cost values close to the wind power or even higher. However, these techniques used to study the generation alternatives, even when considering the externalities and avoided cost and emissions, tend to ignore the interaction between all the elements in the electricity system, which are fundamental for long range planning. The present study intends to go beyond the economic evaluation of the individual electricity generation options. The presented models allow dealing with a complex and dynamic model, recognising that planning and operating decisions regarding one generation option should not be taken individually, because this will strongly affect the entire system.

The aim of the electricity planning models was to provide a description of the Portuguese electricity system in a 10 year period, giving particular emphasis to the coal-natural gas-wind power mix. The models allowed the presentation of a plant scheduling for a large range of CO_2 scenarios, describing the role of thermal and wind power production. Comparison of the models have shown that wind power will affect CCGT performance and not taking into account this element will result in overestimation of the economic and environmental value of wind power.

The difficulties in data collection and in the modelling process, required the assumption of simplifications in the models. However, the presented models have made some important contributions and can give a global overview of the future of the electricity system in Portugal under the assumed constraints, in view of the expected demand and of the fuel prices. Regardless of all the limitations, the NLEPM may be seen as an exploratory model that succeeds on demonstrating the need to develop integrated planning tools for medium to long term electricity planning.

V.8.1 Limitations and research requirements

The present models include only two objectives: cost and CO_2 emissions. Future models may be extended to include other objectives, in particular from the environmental field. Also, the model may be refined to allow for the integration of other renewable energy sources or clean coal technologies as additional variables. The possibility of CO_2 capture for thermal power plants must be regarded. According to the model, surpassing the present Kyoto commitments would imply keeping coal power production at very low levels or even disinvest completely on it. This would represent an important risk from the security supply point of view with an almost exclusive reliance on natural gas. Sustainable coal technologies can overcome the environmental problems of ordinary coal power plants and must be included in the model as another option for clean electricity production. In fact, the recent EU documents (Commission of the European Communities, 2007a) indicate that not only renewable energy is a priority but also the introduction of CO_2 capture and storage.

The NLEPM coupled the results of the analysis of the Portuguese electricity system in 2016, with the dynamic planning process for the 10 year period. Ideally the 2016 strategies should be designed using small periods of analysis, which should capture the instantaneous effect of wind on the operation of conventional thermal power plants. An important limitation of this approach is the theoretical assumption that the results obtained from the 2016 exploration planning could be generalised and included in the planning model. This rough approach treats the CCGT system as a whole and models the operating conditions according to general behaviour of a set of groups. It assumes that the impact of wind on the CCGT system would be the same regardless of the system characteristics and that the performance of coal power plants would remain unaffected regardless of the installed wind power.

Ideally, the process should be iterative and based on a complementary approach, combining long term energy expansion plans with the results of short term operation strategies for each one of these plans. This approach allows for the inclusion of wind power impacts on the system performance within long term capacity expansion and electricity production planning, as described in Figure 5.17. For this particular study, the long range planning could be conducted for a 10 year period divided in monthly intervals. The short term planning should be conducted for a one year period divided in periods of an hour length for more effectively capture the wind power variability.

Further development of the Portuguese model would strongly benefit from close collaboration with the system manager, and further attempts will be made to involve this entity in the process with particular emphasis on the dispatching rules. In a recent study, Rosen et al. (2007) recognise the importance of this issue and present new tools for the integration of wind power effects on power plant scheduling with the optimised evolution of the future power system structure. This desirable collaboration with the system manager would also help developing future versions of the models taking into consideration two other essential aspects: (i) the integration of the Portuguese electricity system in the Iberian market and consequently the possibility of trading with Spain and (ii) the estimated grid costs for integration of decentralised electricity producers.

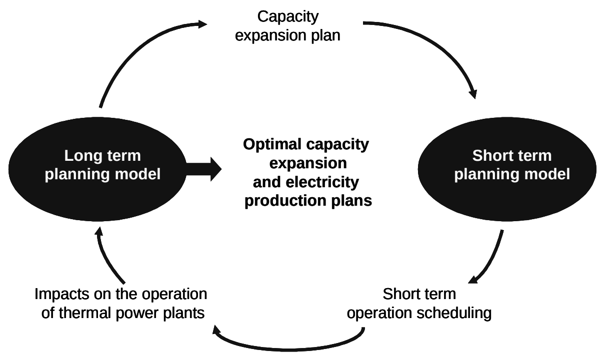

Figure 5.17- Proposed model coupling long and short range planning.

The resource planners' task is now much more complex and along with dealing with several technological options and uncertainty, resource planning must also take into consideration that the objectives expanded beyond cost and even beyond direct environmental impacts (Hobbs, 1995). So far, the study considered a multiple objective energy planning optimisation model where the environmental and economic objectives were described by mathematical functions. The results were a set of compromise solutions detailing plans for new thermal and wind plant installations over a ten year planning horizon for Portugal. However, finding the Pareto optimal solutions is just the first step to resolve the planning problem. A broader multi-perspective evaluation approach is fundamental, measuring and assessing the qualitative impacts of the possible power scenarios and their social acceptability. The subsequent stage of the research was more oriented towards the agents' perspective and called for additional information, based frequently on non technical, qualitative and experience driven factors. The social dimension of the problem was addressed by a participative process, collecting value judgments regarding the definition of the most relevant impacts and their importance.

CHAPTER VI

INTEGRATING SOCIAL CONCERNS INTO ELECTRICITY PLANNING

This chapter proposes a support framework, combining Delphi and AHP methodologies, to accommodate social concerns in the electricity planning process. The process calls for the involvement of a group of experts, participating in the social evaluation of the electricity generation options. The results highlight the complexity and subjectivity of the issues in question, but also suggest that a social impact index may be used as a first indicator of society's acceptance of the plans drawn from the mathematical optimisation models.

VI.1 Introduction

Social, technological, economic and environmental issues should be considered comprehensively in the evaluation of the electricity planning options. The developed electricity planning model (EPM) and non-linear electricity planning model (NLEPM) presented in the previous Chapter, include assessment of quantitative factors, but, do not explicitly consider such factors as noise, visual impact or social acceptance. As highlighted by Söderholm and Sundqvist (2003), many impacts of the power generation sector involve moral concerns and economic valuation provides an insufficient basis for social choice.

In this chapter, the Analytic Hierarchy Process (AHP) and the Delphi methodology are combined to assess the social impact of the different technologies for electricity production. The results of this research may be integrated with the NLEPM, resulting in a new methodology for evaluation of the electricity generation solutions from the environmental, economic and social points of view.

The core elements of the study are the Delphi survey and the AHP analysis. By subdividing the problem into its constituent parts (Analytic Hierarchy), the problem is simplified and allows information on each separate issue to be examined. The relative strength or priority of each objective can be established (Delphi process) and the results synthesised, to derive a single overall priority for all activities (Hemphill et al., 2002).

The combination of the AHP and Delphi has been used in different fields, with the aim of quantifying the value judgment obtained in a group decision making process. Some recent examples include works from Hemphill et al. (2002), on the weighting of the key attributes of sustainable urban regeneration, and Zhong-Wu et al. (2007) for the appraisal of the eco-environmental quality of an ecosystem. Banulus and Salmeron (2007) proposed a Scenario Based Assessment Model integrating both AHP and Delphi methods to support long-term technology policies. Another recent example is the adoption of the Delphi method and AHP for developing an evaluation method to select the optimal location of a regional hospital (Wu et al., 2007). Chen and Liu (2006) presented a new methodology for evaluation and classification of rock mass quality on tunnel engineering based on combined AHP and Delphi methods. Likewise, Hon et al. (2005) combined both methods on a performance evaluation model applied to third party logistics. Liang et al. (2006)

presented a power generation expansion model that uses AHP and Delphi methodologies.

In this chapter we deal with the complexity of the social issues surrounding electricity planning. A methodology is proposed establishing a possible way of allocating weights to the major social impacts and resulting in a final scoring of the electricity generation options. The process involved the following steps:

1. The identification of difficult to quantify attributes and options to analyse. This step corresponds to the definition of the social criteria to select the best electricity generation options, from the social point of view.

2. The establishment of a hierarchical structure. The top of the hierarchy is the main goal corresponding to the social index and the lower levels describe the criteria. On the bottom level we have the discrete alternatives of the problem, corresponding to the electricity generation options.

3. Selection of a group of experts and establishment of the pairwise comparison of the elements of the hierarchical structure. The Delphi method is used to collect this information.

4. Testing the consistency of the data collected from the experts.

5. Aggregation of the scores collected from the experts. From this step results the relative weights of the elements of each level of the hierarchical structure, reflecting the group judgment.

6. Combine the relative weights of the elements of each level of the hierarchical structure, obtaining the final scoring of the electricity generation options against the overall social objective.

This introduction outlines the process of social evaluation of the electricity planning options. The following Sections VI.2 and VI.3 provide a description of the AHP and Delphi methods. Some examples of their application are drawn from the recent literature, justifying also their suitability for the electricity planning problem. The use of these methods for the social ranking of electricity generation options in Portugal is described from Section VI.4 onwards. Section VI.4 describes the hierarchical structure formulation including the options analysed and criteria considered. Section VI.5 details the implementation of the Delphi study based on a questionnaire sent to a pilot group of experts. Section VI.6 combines the information obtained from the Delphi process with AHP in order to derive a social index ranking the electricity generation alternatives. Section VI.7 discusses the results obtained. The incorporation of the social index in the overall planning process is presented in Section VI.8, where the results of this social analysis are integrated with the results of the previous mathematical optimisation procedure, resulting in a new integrated electricity planning model. Section VI.9 draws the conclusions of the chapter pointing out the main limitations of the work and indicating directions for future research.

VI.2 Overview of the AHP method

The AHP addresses and analyses discrete alternative decision problems with multiple conflicting criteria. This technique allows qualitatively based data to be transformed into pairwise comparison data. The decision problem is reduced to a series of smaller self-contained problems. The relative merit of each option is determined from the pairwise analysis of their relative performance ratings. The result of the overall process is a ranking of all the alternatives on an interval scale (Rogers, 2001).

The AHP model uses a hierarchical structure to represent the problem typically representing the overall objective or goal of the decision-making process at the top level, criterion or attribute elements affecting the decision at the intermediate level, and the decision options at the lower level (Nigim et al., 2004). The user chooses weights by comparing attributes two at a time, assessing the ratios for their importance. These ratios are used not only to compute the weights of individual attributes, but also to measure the consistency of the user's assessments (Hobbs and Meier, 2003).

Zhong-Wu et al. (2007), considered AHP to be a simple systematic engineering method to quantitatively analyse non-quantitative criteria. The method incorporates the researcher's subjective judgment aided, if needs be, by expert opinion during the analysis, and by expressing the complex system in a hierarchical structure. Thus, AHP assists the decision-making process to be systemic, numerical and computable. Also, it assesses the consistency of the judgment and incorporates the evaluations of all decision makers into a final decision, without having to elicit their utility functions on criteria (Wu et al., 2007). According to Liang et al. (2006) "AHP is a systematic method that captures a human being's mind process in mathematically hierarchical levels".

AHP is a popular method in problem evaluation (see for example Hobbs and Meier, 2003, Limmeechokchai and Chawana, 2007 or Liang et al., 2006) and has been extensively applied in dealing with complex energy and environmental problems. Pohekar and Ramachandran (2004) presented a literature review on multi-criteria decision making on sustainable energy planning, and observed that AHP is the most popular technique.

Hobbs and Meier (2003), give some examples of AHP usage in the evaluation of the environmental impacts of power planning options, in the selection of greenhouse mitigation options, in the evaluation of electricity supply plans and in the development of national energy policy. Lee et al. (2007) used an AHP approach to determine priorities in technology development for energy efficiency and greenhouse gas control plans in Korea. Liang et al. (2006) included AHP in their model for evaluating power generation projects. Other examples in energy related sectors include: the prioritisation of barriers to energy efficiency in small industry clusters (Nagesha and Balandra, 2006), the identification and prioritisation of barriers to particular sustainable energy development strategies (Limmeechokchai and Chawana, 2007), the prioritisation of local renewable energy projects (Nigim et al., 2004) or the prioritisation of energy conservation policy instruments (Kablan, 2004), among many others. An extensive list of examples may be found in Greening and Bernow (2004) or Pohekar and Ramachandran (2004).

VI.2.1 The AHP process

The analytical hierarchy process was developed by Saaty (1980) and is based on the formulation of the decision problem in a hierarchical structure, like the one presented in Figure 6.1. The process involves the following main steps:

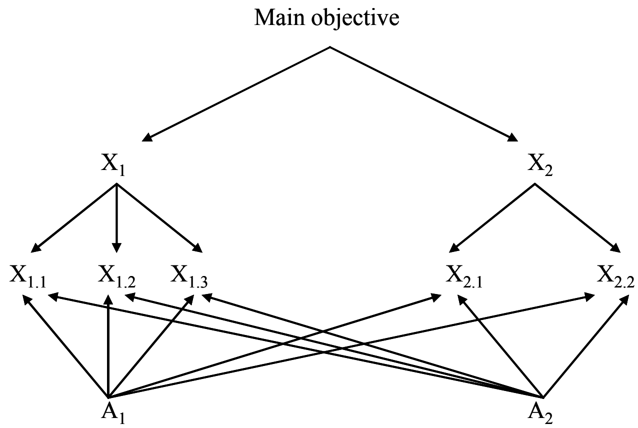

Figure 6.1- Hierarchy tree.

(1) Subdividing the problem into a hierarchy, with the main objective placed in the top vertex, the criteria and sub-criteria placed in the intermediate levels and the alternatives placed on the bottom level. Figure 6.1 represents an example of a simple hierarchy tree, where X_1 and X_2 are two criteria, $X_{1.1}$, $X_{1.2}$ and $X_{1.3}$ are the sub-criteria associated with X_1 and $X_{2.1}$, $X_{2.2}$ are the sub-criteria associated with $X_{2,}$ and A_1 and A_2 are the discrete alternatives.

(2) Pairwise comparison of the elements in each level with respect to their importance to each of the higher-level elements to which they are linked. For example elements, $X_{1.1}$, $X_{1.2}$ and $X_{1.3}$ are pairwise compared concerning their importance with regards to X_1 criterion and the process will be repeated at each level until reaching the top of the hierarchy. This step should also include the computation of the consistency ratio of the matrix of judgments to make sure that the judgments are consistent.

(3) Estimation of the global contribution of each alternative to the main objective, by the aggregation of the comparison levels identified in step (2).

Thus, the AHP involves the estimation of the relative importance of each criterion and sub-criterion evaluated in numerical scales (importance ratios) and the estimation of the relative performance of each alternative on each of the sub-criteria evaluated also in numerical scales (preference ratios). Greening and Bernow (2004) pointed out that the key challenge in the AHP approach is reaching agreement among the decision makers on value judgements of the importance of the elements.

Hon et al. (2005) describes the major steps of the AHP methodology: build pairwise comparison matrix, eigenvalue and eigenvector calculation, review of the consistency of the matrix and normalize criteria weight. These authors consider that the AHP method obtains a weighting of the criteria through the paired comparison between every criteria pair within each level, which is more credible and more objective than overall subjective judgments set directly by decision making managers.

The values used for the pairwise comparison are usually based on Saaty scale of preferences, presented in Table 6.1.

Table 6.1- Saaty's scale of preferences in the pairwise comparison process (Saaty, 1980)

Score	Pairwise evaluation
9	A absolutely more important than B
7	A is very strongly more important than B
5	A is strongly more important than B
3	A is moderately more important than B
1	A is equally important to B
1/9, 1/7, 1/5, 1/3, 1	Reciprocal values

For this particular research, the aim was to address the negative social impact of each generating technology[86]. For the comparison a scale based on Saaty (1980) proposal was used, detailed in Table 6.2.

Table 6.2- Scale preferences used in the pairwise comparison process.

Range	Category
Superior	Absolutely superior
	Very strongly superior
	Strongly superior
	Moderately superior
Equal	Equal
Inferior	Absolutely inferior
	Very strongly inferior
	Strongly inferior
	Moderately inferior

Table 6.3 represents a pairwise comparison matrix, with the elements representing the quantified judgment on a pair of solutions. The matrix used in the example was drawn from the results obtained for the pairwise comparison of the three possible generation

[86] A particular technology assigned a higher score is considered "worst" from the social point of view than a technology assigned with lower score.

technologies against noise impact, provided by one of the experts.

Table 6.3 - Pairwise comparison of the alternatives with respect to the noise impact.

	Coal	Gas	Wind
Coal	1	1	1/3
Gas	1	1	1/5
Wind	3	5	1

When an alternative is compared with itself each alternative has equal weight. This makes the diagonal elements of the matrix always equal to 1. The entries below the diagonal are the reciprocal of those entries above the diagonal. This implies that only the judgements in the upper triangle of the matrix need be solicited (Kablan, 2004). The matrix above (Table 6.3) shows for example that for this expert, the noise impact of coal solution is equal to the noise impact of gas solution. The noise impact of the wind solution is strongly superior to the noise impact of the gas solution and moderately superior to the coal solution[87].

For the computation of the weights AHP follows the eigenvector analysis, as described in Kablan (2004). Assuming that the decision maker is capable of making pairwise comparasions between different alternatives ($A_1, A_2, \ldots A_n$), these may be represented as in the following matrix:

$$A = \begin{array}{c} \\ A1 \\ A2 \\ .. \\ An \end{array} \begin{array}{c} \begin{array}{cccc} A1 & A2 & .... & An \end{array} \\ \begin{bmatrix} a11 & a12 & ... & a1n \\ a21 & a22 & ... & a2n \\ ... & ... & ... & ... \\ an1 & an2 & ... & ann \end{bmatrix} \end{array}$$

The values assigned to a_{ij} are usually in accordance with Saaty scale presented in Table 6.1. A is then a consistent matrix of judgment and Saaty's (1980) method computes K (vector of weights) as the principal right eigenvector of the matrix A:

[87] Wind technology is then considered "strongly worst to society" than gas technology, from the noise impact point of view. The same way, wind technology is considered "moderately worst to society" than coal technology, from the noise impact point of view.

$$\begin{bmatrix} a11 & a12 & ... & a1n \\ a21 & a22 & ... & a2n \\ ... & ... & ... & ... \\ an1 & an2 & ... & ann \end{bmatrix} \begin{bmatrix} W1 \\ W2 \\ ... \\ Wn \end{bmatrix} = \lambda \begin{bmatrix} W1 \\ W2 \\ ... \\ Wn \end{bmatrix} \quad \text{or } AK=\lambda K \qquad (6.1)$$

$$(A-\lambda_{max}\ Z)K=0 \qquad (6.2)$$

Where λ_{max} is the largest possible value of an eigenvalue (λ) of matrix A and Z is the identity matrix and K is the eigenvector.

If the pairwise matrix is perfectly consistent then λ will be equal to the number of alternatives under consideration (n). The consistency index (CI) and the random consistency index (CR) may be computed by (Kablan, 2004):

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad (6.3)$$

$$CR = \frac{CI}{RI} \qquad (6.4)$$

The consistency ratio is a measure of how a given matrix compares to a purely random matrix in terms of their consistency indices. The value of the random index (RI) may be obtained from published tables for each size of the matrix, n (see for example Kablan, 2004 or Lee et al., 2007). In practice if CR≤0.10, the consistency of this matrix is acceptable (Zhong-Wu et al., 2006; Hon et al., 2005, Kablan, 2004).

For the computation of the weights and the consistency ranking, the software package Super Decisions was used. This software was developed by the Creative Decisions Foundation and is freely available in the internet (http://www.superdecisions.com). The input to the software is the hierarchical structure of the problem and the pairwise comparison matrices of the attributes. The output includes the weighting matrices, the evaluation of the consistency of the judgments and the final ranking of the options.

For the particular example of matrix A presented in Table 6.3, Saaty's (1980) method may be applied to derive the vector of weights detailed in Table 6.4 along with the consistency ratio:

$$\begin{bmatrix} 1 & 1 & 1/3 \\ 1 & 1 & 1/5 \\ 3 & 5 & 1 \end{bmatrix} \begin{bmatrix} W_{coal} \\ W_{gas} \\ W_{wind} \end{bmatrix} = \lambda \begin{bmatrix} W_{coal} \\ W_{gas} \\ W_{wind} \end{bmatrix} \tag{6.5}$$

Table.6.4 – Vector of weights of the alternatives with respect to the noise impact.

	Noise impact
Gas	0.156
Coal	0.185
Wind	0.659
CR	*0.0280*

As expected, the weights sum to 1.0. For this particular expert as far as noise is concerned, gas is the most desirable solution, followed by coal generation plants with wind generation being the least desirable. Since the consistency ratio is below 10% then the judgements are considered consistent, although the consistency is not perfect. In perfect consistency conditions, if the noise impact of the coal solution is equal to the noise impact of the gas solution, the score between the coal and gas solutions respectively with the wind solution should be the same. If that were the case, the CR would equal zero.

VI.2.2 Suitability of the AHP approach.

The AHP is especially suitable for complex systems where multiple options and multiple criteria are to be taken into consideration. The computation of a social index for a complex problem like the electricity generation options involves individual judgments and it can be described and analysed using a hierarchical structure. The AHP was selected because of its simplicity and ability to deal with qualitative/subjective data. The qualitative scale used simplifies the judgement but at the same time allows for the mathematical treatment of the results. The final outcome is the global ranking of the options.

AHP is recognized as a robust and flexible tool for dealing with complex decision making problems (Liang et al., 2006) and its use has been largely explored in the literature with many examples in the energy decision making field. This method is well suited for group decision making (Lai et al., 2002) and its integration with the Delphi method is also well documented (see Section VI.1). Using the hierarchical structure, the experts compare the electricity generation options against different criteria. It is possible to recognize conflicts among experts for each element of the hierarchy, how it affects the final ranking and also the consistency of the judgments.

VI.3 Overview of the Delphi method

The main objective of the Delphi technique is to describe a variety of alternatives and to provide a constructive forum in which consensus may occur (Rayens and Hahn, 2000). The three basic conditions of the process are: anonymity of the respondents, statistical treatment of the responses and controlled feedback in subsequent rounds.

The anonymity of the answers gives group members the freedom to express their opinion, avoiding possible negative influences due to previous assumed positions, status of the participating experts and reluctance on assuming positions different from the general opinion or from a dominant group.

The statistical treatment of the responses allows the assembly of collective information. This phase feature ensures that all the opinions form part of the final answer and that these opinions may be communicated to the panel without revealing individual judgments. Delphi study presents the statistical result that includes the opinion of the entire group, presenting both the centre of the group opinion and the degree of spread about the centre (Institute for Prospective Technologic Studies, 1996).

The experts must be consulted at least twice so that they may reconsider their answer, aided by the information received from other experts. This feedback is controlled, so that all irrelevant information is eliminated (Landeta, 2006) and the panel individuals have access to the responses of the whole group as well as their own response for reconsideration. Often, feedback is presented as a simple statistical summary of the group response, usually comprising a mean or median value. Occasionally, additional information may also be provided, such as arguments from the individuals (Rowe and Wright, 1999a).

The interaction among group members taking place in a controlled and anonymous manner distinguishes Delphi from the conventional face-to-face interaction. At the end of the procedure the group judgement is taken as a statistical measure of the participants' estimates. This final judgement may be seen as an equal weighting of the opinions of the participants (Rowe and Wright, 1999a).

The basic sequence of the Delphi method may be resumed as an interactive questionnaire that is passed around several times in a group of experts, keeping the anonymity of the individual responses. In the first round the experts receive a written questionnaire or are asked to participate in a interview. This first questionnaire usually describes in detail the issue in question and contains information that may help the respondents to answer the questions and ensures a reasonable homogeneity of the knowledge and language used (Wright and Giovinazzo, 2000).

The initial measurement of opinions is followed by the data analysis. Based on the group responses to the first questionnaire, a new questionnaire is developed where the statistical results of the first round and information on the beliefs of other participants are presented. This process allows participants to reconsider their opinions in light of the views of the other elements of the panel and may be repeated until consensus is reached or the polarisation is well established (Rayens and Hahn, 2000). When participants reach consensus in a question, it is omitted from succeeding iterations (Alberts, 2007).

As Wright and Giovinazzo (2000) stated the Delphi is not a statistical representative study but a process of collecting opinions from a group of experts, who from their knowledge and exchange of information may achieve comprehensive opinions on the proposed questions. This issue is also pointed out by Okoli and Pawlowski (2004), who underlined that the questions that a Delphi study investigates are those of high uncertainty and speculation. Thus a general population or sample might not be sufficiently knowledgeable to answer the questions accurately.

The Delphi method is frequently used to forecast tendencies and future events. Matias (2002) used a Delphi approach on the design of future energy scenarios in Portugal. Blind et al. (2001) used a two round Delphi expert survey focusing on the estimation of the future development of science and technology in Germany. The Institute for Prospective

Technological Studies refers and uses the Delphi method as a forecasting tool (see for example Institute for Prospective Technological Studies, 1996, 2000 and 2002). Iniyan and Jagadeesan (1997) used a Delphi study to determine the social acceptance and percentage use of renewable energy sources in the future. A Delphi study was also conducted for the assessment of changes in the international business environment over the next decade and the evaluation of the impact of these changes on policy and on corporate practices (Czinkota and Ronkainen, 2005).

However, as stated by Rayens and Hahn (2000), Delphi technique is also an appropriate tool for the definition of policies and for decision making, enabling the description of agreement on specific policy options (policy Delphi). OECD (2006) suggests some examples of tools that could be used in the context of strategic environmental assessment approaches. This report points out that expert judgement of direct and indirect impacts is relatively quick and cheap and that it can be used in applications like collecting data, developing alternatives from the strategic policy level to the detailed site level, analysing and ranking them, predicting impacts, and suggesting mitigation measures. Also the Guide for evaluation of socio-economic development in Europe (Tavistock Institute, 2003) includes Delphi panel as a key method for interventions in the energy sector.

Rayens and Hahn (2000) report the use of policy Delphi method in building consensus on tobacco policy issues in Kentucky. Also Jillson (2002) describes a previous study conducted in the USA, using Delphi procedures in the exploration of the national drug-abuse policy that has raised considerable interest in the utilisation of the technique not only in the drug-abuse field, but in other social policy areas as well. Wright (2006) describes a Delphi method used on the generation of an implementation plan for university sustainability policies. Loe and Wojtanowski (2001) used a two-round policy Delphi survey for assessing the associated benefits and costs of the Canada's Flood Damage Reduction Program. Okoli and Pawlowski (2004) presented some examples of publications using the Delphi method as a tool in information systems research to identify and prioritise issues for managerial decision-making and to forecast the business future. The Lawrence Technological University conducted Delphi inquiries on how to address wind turbine noise and potential wildlife impacts (Alberts, 2007). The participation on the study was opened to public, including stakeholders, public policy makers and concerned citizens. However, the results showed that participants with insufficient experience were unable to participate effectively in the decision making process, demonstrating that it can be more productive to seek input from technical experts than to seek consensus from all stakeholders.

VI.3.1 The Delphi process

Figure 6.2 summarises a general Delphi process.

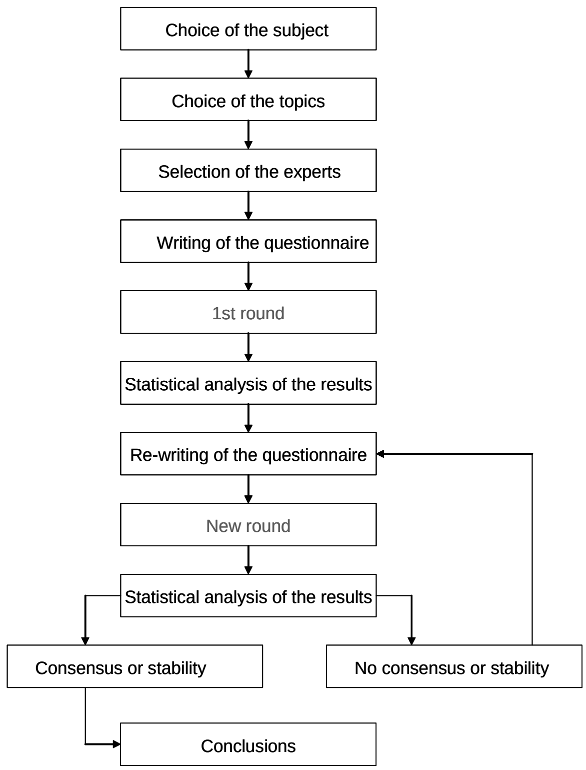

Figure 6.2- General Delphi process.

The first phase is characterised by the description of the subject to study and of the objectives of the research. Based on this, the specific topics to be addressed are defined and the experts are chosen. The selection of the experts is a crucial phase because the quality of the results depends heavily on the knowledge and commitment of the participants. According to Scapolo and Miles (2006), the minimum size of a panel of experts to involve in a Delphi exercise should be no less than 8 to 10. Rayens and Hahn (2000) also indicate that in a typical policy Delphi the number of participants varies between 10 and 30.

The research team contacts the experts explaining them the basis of the Delphi technique, the objective of the research and their role in the process. Usually the questionnaires are sent by post or email although collecting the responses with in-person interviews may also be possible. The responses of this first round are collected and the research team proceed to the statistical analysis. After analysing the results a new questionnaire is elaborated. The participant's response on the first enquire determine modifications through each iteration (Alberts, 2007). The new questionnaire presents the results of the first round; it frequently includes comments received during the first round, new questions may be added and some other questions may be eliminated.

The rounds continue until a satisfactory level of convergence is achieved. According to Wright and Giovinazzo (2000), at minimum the study should have two rounds and usually is does not overcome three rounds. Alberts (2007) refers that the ending of the process may depend not only on reaching consensus but also on project funding. Scapolo and Miles (2006) restricted the number of rounds to two, in order to limit as much as possible the weariness of the participants and their possible pressure for conformity. Also Rayens and Hahn (2000) limited the policy Delphi process to two stages due to potential for participant attrition and budget constraints.

The approach to measuring consensus varies from study to study. Rayens and Hahn (2000) present some examples of measures used in past studies such as:

- The frequency distributions. The criterion of at least 51% responding to a certain category may be used to determine consensus, or at least 67% in a yes-no study, as presented in the following example for two possible questions.

Example 1

Question A		**Question B**	
Response	*% of responses*	*Response*	*% of responses*
Strongly agree	20%	Agree	80%
Agree	58%	Disagree	20%
Neither agree or disagree	4%		
Disagree	15%		
Strongly disagree	3%		
Consensus	Achieved	**Consensus**	Achieved

- In studies where the participants are asked to rank or weight ideas, the mean values and standard deviation may be computed in each round. A reduction of the standard deviation indicates higher degree of consensus achieved after successive rounds.

- Another popular approach is the interquartile range (IQR), measuring the absolute value of difference between the 1st and 3rd quartile, with smaller values indicating higher degree of consensus. The interpretation of this measure varies between authors and of course depends on the number of response choices. Rayens and Hahn (2000) identified an IQR of 0.00 as an indicator of consensus. These authors assumed also that consensus was achieved if the IQR was equal to 1.00 and the percentage of generally positive or negative responses were higher than 60%. By using this strategy the authors could deal with a larger number of response choices or categories. An example is presented next:

Example 2

Question A		**Question B**	
Response	*% of responses*	*Response*	*% of responses*
Strongly agree	49%	Strongly agree	21%
Agree	39%	Agree	61%
Disagree	11%	Disagree	16%
Strongly disagree	1%	Strongly disagree	2%
IQR	1.00	**IQR**	0.00
Consensus	Achieved	**Consensus**	Achieved

In a different work, Loe and Wojtanowski (2001) assumed:

- high consensus if at least 70% of the participants chose one particular category or at least 80% of the participants chose two related categories,
- low consensus if at least 50% of the participants chose one category and 60% of the participants chose two related categories and
- no consensus for less than 60% rating in two related categories.

Dorussen et al. (2005) also detail some measures of agreement in experts interviews. However, these measures only apply if the number of possible answer categories is fairly small. In their study the experts were asked to choose between two and five possible categories. Rowe and Wright (1999b) present an analysis of some measures extensively used in the literature to determine consensus achievement, including the variance reduction and the post-group consensus.

Most Delphi studies are consensus oriented and it is assumed that this consensus is achieved when a certain percentage of answers fall within a certain category or a certain value of IQR is achieved. Scheibe et al. (2002) indicate as a possible IQR cuttoff value two units in a ten unit scale. These authors also present an additional measure which takes into consideration the stability of the respondents' vote distribution curve over successive rounds of the Delphi. This way the method measures the amount of change in the group opinion rather than the amount of change in each individual's vote between rounds. The authors propose the 15% change level as the 'state of equilibrium'.

Combining the stability and consensus measures allows the identification of well defined disagreement aspects as well as aspects of agreement within the participating group. As Landeta (2006) pointed out, the restriction of the obligatory search for consensus may be eliminated and the Delphi technique may be described as a social research technique which aim is to obtain a reliable group opinion using a group of experts. Linestone and Turoff (2002) also characterise the Delphi technique as "a method for structuring a group communication process (…) allowing a group of individuals, as a whole, to deal with a complex problem". Landeta (2006) draws attention to the contrast between the apparent simplicity of the technique and the work and difficulty involved in its execution. These difficulties include ensuring the initial collaboration of the experts and particularly their commitment to the process in different rounds.

A more detailed description of the Delphi method may be found in Linstone and Turoff (2002), along with its historical development and examples of application. Also Landeta (2006) reviews the literature in this area and presents some examples of application. Rowe and Wright (1999b) compile published studies involving evaluation of the Delphi technique.

VI.3.2 Suitability of the Delphi approach

The Delphi method was selected for information collection in this particular research for the following reasons:

- The questions addressed are complex and highly subjective. Using a panel of experts with previous knowledge and interest in the matter in question seems to be the most productive way to collect opinions.

- The anonymity of the responses eliminates the influence of dominant position, the conflict between participants or the reluctance on changing previous assumed positions. But as the participants are only anonymous to each other and never to the researcher, it facilitates the follow-up process. In fact, this allowed phone contact with the non respondents increasing the response rate.

- The structured questionnaire ensures a proper collection of information, in a way that may be easily incorporated in the AHP analysis.

- It does not require the experts to meet physically, which allows them to answer the questioner in their own workplace and when they find appropriate.

- The Delphi process is a time consuming task, due to the iterative process. However for this particular research, the panel size was kept modest and the questionnaires were sent by email, which allowed the process completion in about three months.

- The literature indicates that the non-response is typically low in Delphi surveys (Okoli and Pawlowski, 2004).

VI.4 Hierarchical structure formulation

As the analysis is to be carried out using the AHP a hierarchical structure describing the problem must be designed. For this elements of the different levels of the hierarchy and their relationships must be identified.

VI.4.1 Options or alternatives.

The process started with the identification of the options to be analysed. Based on the optimisation models presented in chapter V, three electricity generation options were included: coal, gas and wind. However, we do not expect the development of the Portuguese electricity system to be based only on one of these generation options, and the most probable scenario will include the combination of the three technologies.

For comparison of the alternatives the evaluation was based on the marginal increase of the demand and the corresponding increase of each one of the generation options. For a marginal increase of 1000 MW of the electricity demand[88], the corresponding increase of the generation options was defined. From the AHP analysis, a social index representing the social evaluation of these options may then be obtained. The overall social evaluation of the possible combined scenarios will be drawn from these individual indices.

VI.4.2 Criteria

The next step was the identification of the criteria to be included in the evaluation process. Choosing these criteria is essential for the proper establishment of the social index. The criteria should be able to represent the main social (or non quantifiable) features of the system. From existing literature addressing the social impact of the electricity generation technologies and from discussions with experts in the energy field, the criteria considered relevant were defined.

The public perception of wind power is addressed by several authors for a number of countries or regions. Some examples of research studies on this field include Ek (2005), Wolsink (2000), Manwell et al. (2005) or Bergmann et al. (2006) among many others[89]. Most of the studies identified as positive aspects the renewable characteristic of wind power and the avoided emissions. On the other hand, in most of the publications there is a predominant emphasis on the negative visual impact on the landscape. Other identified negative impacts include: the impacts on wildlife, the noise pollution, the unreliability of wind energy supply and the possible financial cost, with particular emphasis on the first two aspects.

Studies addressing the coal and gas power plants impacts deal mainly with the cost and environmental emissions (see Rafaj and Kypreos, 2007 or Soderholm and Sundqvist, 2003). The environmental impact usually focuses on the damages caused to health and on the impact on climate change. In the ExternE project, the external effects from coal and natural gas power plants were mainly associated with their pollutant emissions and their impact on public and occupational health, agriculture and forests. The noise problem was also pointed out, including operational and traffic impact.

[88] This value corresponds to about 17% of the average load in 2006.
[89] This issue is longer debated in Section IV.3.3 of this thesis.

VI.4.2.1 Semi-structured interviews with experts

Following the literature analysis, semi-structured interviews were conducted with experts from the academic field, energy consultants, members of environmental associations, environmental public organisms' staff and researchers. Nine interviews were conducted, aiming to evaluate the importance of each of the criteria or to identify some others and helpful opinions and suggestions were collected.

The interviews addressed the following issues:

- The general public reaction towards wind power, coal and natural gas power plants and the opinion of local populations.
- The major complains expressed by the population in what concerns wind, coal and natural gas power plants.
- The major benefits that new power plants may bring to local populations.
- The most important aspects to be taken into account for the electricity planning in Portugal
- What the experts felt would be the desirable and expected future scenarios for electricity power sector in Portugal.

The experts were invited to comment these themes, departing from initial questions posed by the researcher.

The experts were asked about the public opinion towards wind, coal and gas power stations. All of them believe that in general the attitude towards wind power in Portugal is positive, with only a few small focus of resistance. Most of the experts also argued that financial gains for the population living near the wind farm play a very important role on the acceptance and interest for this technology. The opposition, when existing, would come mainly from a few outsiders and occasional visitors that might express some concern with the scenic beauty and with no direct financial interest on a particular wind farm.

Most of the experts believe that the majority of the population do not have opinion on the impact of the thermal power stations and wind farms. One expert stated that opinion on gas or coal may be less negative, because these are centralised power stations with resistance confined to the particular location of the plants. However, a few other experts think that coal and gas power plants are associated with environmental damages and that the population is aware of the environmental advantages of wind. In Portugal, most of the wind power stations are located in hills on low income land. Some of the experts, who have direct contact with the population, think that locals tend to see wind farms as a positive way of contributing to the country technological development, making good use of land that otherwise would not be useful and bringing financial resources to the community.

Members of environmental associations expressed concern for two other adverse impacts related to wind power plants: the alteration of migrant birds' route habits and the change on habitat conditions in protected areas. This last aspect is especially associated with the construction of roads giving access to areas formerly protected from human interaction.

When asked about other gains brought by wind power plants, the experts pointed out, at national level, the reduction of external energy dependency and at local level, the construction of new road infrastructures, the development of small local businesses and the financial gains for the owners of the land. The major complaints on wind power plants are due to noise. As argued by one of the experts, the noise levels may be measured but the sensitiveness of the population is highly subjective and unpredictable.

Most of the experts, believe that locals do not have a negative perception of the visual impact of wind power stations. This is not an unexpected outcome. Although landscape protection is a key priority in regions like England or Scotland, in other countries like Spain there is little activity to protect landscapes. In Spain studies revealed that the impact of wind farms on flora and fauna or specific local impacts on geologically rare cliff sites are considered more important than landscape changes (Toke et al., 2007).

When asked about what they thought were the most important aspects to take into consideration during energy planning, all the experts indicated external energy dependency. Two of them pointed out the need to incorporate into the analysis not only the external energy dependency but also the technological external dependency. Some of the experts also expressed concern about atmospheric pollution, cost and impact on birds and wildlife. Only one of them mentioned the visual impact.

The main conclusions from the interviews seem to indicate that the Portuguese population is still ill informed about the electricity generation options and have no clear opinion on this subject. Most of the experts believe that there is a global support for wind power and that it will be possible to increase the installed power without strong opposition from the population.

VI.4.2.2 Selection of the criteria

Based on the literature and on the interviews, the following non quantitative criteria were chosen for the social evaluation process:

- **Noise impact**. This impact is often referred on the literature as an important criterion to take into account in the valuation of wind and thermal power plant projects. The interviews also revealed that this is a critical issue for the Portuguese population and, that most complaints, when existing, are due to the noise impact of the energy projects.

- **Impact on birds and wildlife**. The experts also revealed concerns about this impact, in particular in relation to wind power projects. It is also stressed in most international studies and included in the list of potential disadvantages.

- **Visual impact**. According to the interviews, this aspect seems to be still of minor importance in Portugal. However, with the expected increase of wind turbines people may become more aware of its presence and the aesthetical concerns may become more important. For this reason and also because this is the strongest impact reported in international literature, it was decided to include it in the analysis.

- **The social acceptance**. The experts' interviews indicate that public opposition is not a fundamental criterion to take into account during the energy planning process. However, Wolsink (2007) for example, emphasised the need to take into consideration public attitude on wind implementation decisions, not only at a general level but also at the local project level and stressed the importance of including the public in the decision making process. Also Cavallaro and Ciraolo

(2005) support that social acceptability is extremely important since it may heavily influence the amount of time needed to complete the energy project. The public acceptance of a project may not be sufficient to ensure its viability, but represents a clear contribution to its success. This last criterion aims to synthesise the experts' perception of the general social acceptance of the electricity generation alternatives.

As the questionnaire will involve pairwise comparisons, the number of criteria included was limited, avoiding a long and complex process that might reduce the experts' willingness to participate. The AHP analysis will only focus on the qualitative criteria. Aspects like cost, external energy dependency and pollutant emissions, although mentioned by the experts, were already quantified and included in a mathematical formulation. The cost and CO_2 emissions are part of the EPM and NLEPM optimisation process and the external dependency of the electricity generation sector was computed from the share of imported energy sources (including electricity imports) used for electricity production.

Combining the options and the criteria, the hierarchical structure of the problem may be represented as in Figure 6.3.

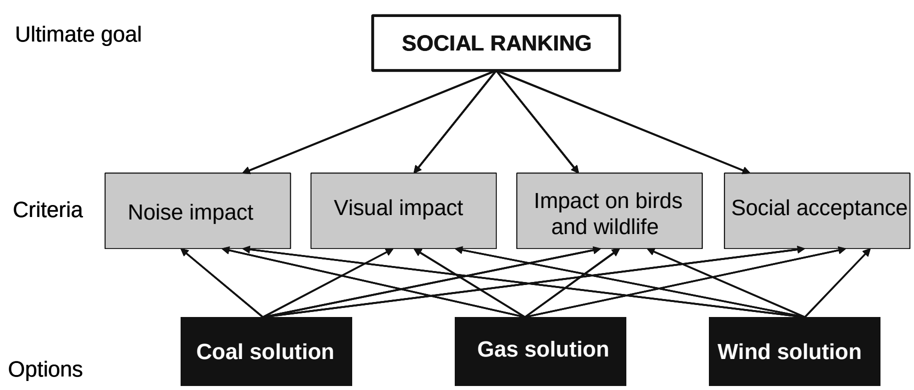

Figure 6.3 - AHP model for the prioritisation of electricity generation options.

The experts were asked to give their individual view on the pairwise comparison of criteria and options. For the social acceptance criteria the experts were expected to give their response based on their experience and on what they perceive is the view of the population.

VI.5 Delphi implementation

Figure 6.4 summarises the Delphi process followed to assess experts' opinions on the social impact of the electricity generation technologies in Portugal.

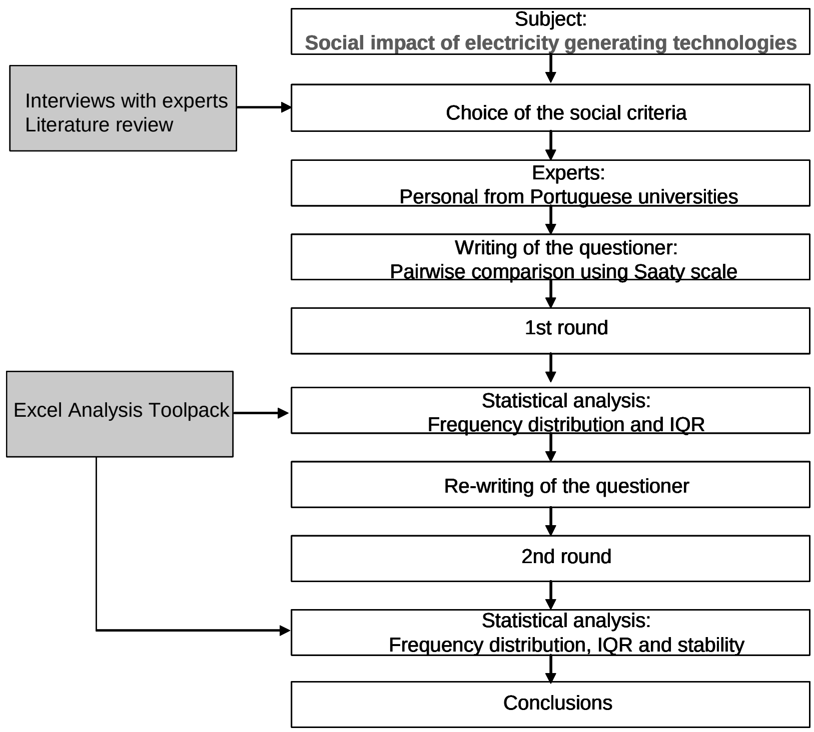

Figure 6.4 - Delphi process for the social evaluation of electricity generation options.

The process began with the definition of the objective and of the criteria to be included in the social evaluation of the different electricity generation technologies in Portugal, as described in section VI.4. The final outcome was the hierarchical structure and the description of the pairwise comparison to be conducted. The focus of the Delphi process was on the comparison of three electricity generation technologies (wind, coal and natural gas) in what concerns their major impacts from the social point of view.

The experts were selected from Portuguese universities. With the support of the internet, university staff involved in energy projects or lecturing subjects on this area were identified. Additional experts came from contacts made in the course of the research. The procedure identified 12 experts who would be appropriate to include in the pilot group. Although all the experts came from the same professional field they have different opinions and hold a variety of positions for and against each one of the options analysed.

Two of the experts tested the questionnaire before sending it to the pilot group, in order to check the time taken to complete it, to ensure the homogeneity of the language used and the clearness of the issues in question and of the scale used.

VI.5.1 First questionnaire

The first questionnaire, sent to experts in December 2006, may be found in Annex 12. The questionnaire asks the experts to assume the need to increase the available power by about 1000 MW. This may be done by increasing the number of coal, natural gas or wind power plants, described as follows:

	Coal solution
Description	2 new coal power plants, one with installed capacity equal to 700 MW and another one with installed capacity equal to 450 MW.
Placement	Close to large electricity consumption centres.
Characteristics	In each power station there will be one chimney 225 m high and one cooling tower. Each power plant may occupy an area of about 1.5 ha (0.015 km^2) and burns imported coal.
Examples	Presently two power stations operate in Portugal: one in Sines and another one in Pego.

	Gas solution
Description	2 new combined cycle natural gas power plants, one with installed capacity equal to 660 MW and another one with installed capacity equal to 400 MW.
Placement	Close to large electricity consumption centres.
Characteristics	The 660 MW power station will have two chimneys. The 400 MW power station will have 1 chimney. All the chimneys will be 80 m high. Each power station will have a cooling tower. Each power station may occupy an area of about 1.5 ha (0.015 km^2). It burns imported natural gas.
Examples	Presently two CCGT operate in Portugal: one in Ribatejo (Carregado) and another one in Tapada do Outerio (Gondomar).

	Wind solution
Description	250 new wind farms, with total installed capacity equal to 3800 MW.
Placement	Spread across the country, but with higher concentration in the inland North hills.
Characteristics	Each wind farm will have between 10 and 15 turbine, about 65 m high and may occupy an area of about 100 ha (1 km^2).
Examples	Presently there are about 1000 turbines operating in the mainland, some examples may be seen in Marão, Açor, Barroso among many others.

The questionnaire also informed about the power plants presently operating in Portugal and along with the questionnaire, three photos of these power plants were sent to the experts.

The first part of the questionnaire focus on the comparison of the three solutions presented according to the social criteria. A brief definition of these social criteria was also included in the questionnaire, as follows:

	Definition
Visual impact	This criterion is difficult to quantify and depends heavily on individual perception. It is associated with the aesthetic aspect, and it will be necessary to assess if the project will bring significant changes to the landscape and if these changes will reduce the visual quality of the region.
Noise level	This criterion is usually associated with sleeping disorders, interference with learning activities and general annoyance, caused by undesirable noise. It will be necessary to assess if the project will change the noise levels in the region.
Impact on birds and wildlife	This criterion is associated with problems like bird electrocution, collision mortality, reduction of available habitat, disturbance of nesting, alteration of migration habits and general habitat disturbances due the increase of human activity.
Social acceptance	This criterion is associated with the way the project will be seen and accepted by the population in general. It may generate some resistance or on the other hand may be considered desirable.

The experts were asked to pair wise compare the three solutions regarding each one of the described aspects using the scale presented in table 6.2.

For example, question 1 presented the description of the visual impact and than asked the experts:

a) The visual impact of the coal solution is [ ] to the gas solution.
b) The visual impact of the coal solution is [ ] to the wind solution.
c) The visual impact of the gas solution is [ ] to the wind solution.

The Delphi questionnaires were written and sent to the experts in a word file and the possible scale for the answer appeared in the drop down form field, in grey in the example. The first part of questionnaire included 12 pairwise comparisons (4 criteria ×3 solutions) .

The second part of the questionnaire focuses on the comparison of the relative importance of the four social criteria. The experts were asked to pairwise compare these criteria, using again the scale presented in table 6.2. The second part of the questionnaire included 6 pairwise comparisons. For example the first question of the second part asked the experts:

a) The visual impact is [▼] to the noise level.

The third part of the questionnaire aimed to clarify if the experts would accept an increase on the average electricity bill, in order to contribute to the reduction of the atmospheric pollution. This represents a proxy measure of how much the experts would be ready to pay to reduce CO_2 levels. This final question will not be included in the AHP analysis but aims to contribute to the definition of allowable ranges for the cost in the optimisation models presented in chapter V.

The experts were informed that in January 2006, the electricity bill of an average consumer in Portugal was about 41 €/month. The question was presented as follows:

How much would you be willing to increase your electricity bill to contribute to the reduction of atmospheric pollution? [▼]

The possible scale for the response also appeared in a drop down field, and the ranges are detailed in Table 6.5:

Table 6.5- Scale of the allowable range of cost increase.

Pairwise evaluation
0% (I am not willing to increase my electricity bill)
Up to 5%
From 6 to 10%
More than 10%

These ranges were based on the European Commission survey "Attitude towards energy" (European Commission, 2006b). In this survey, the European consumers were asked whether they would be willing to pay more for energy produced from renewable sources than for energy produced from other sources. The country analysis of the results revealed that 70% of the Portuguese consumers were not willing to pay more, 21% would pay up to 5% more, and 6% would pay 6 to 10% more (the remaining 3% did not know). The results clearly indicate that Portuguese citizens are reluctant to make efforts in energy consumption demanding higher charges. As so, in our Delphi process only the ranges presented in table 6.5 were considered.

At the end of the questionnaire the expert was invited to comment. This might include justification of the responses, suggestions for the inclusion of other aspects or for improving the questionnaire or any other information that the expert wanted to share. The questionnaires were sent electronically, in an effort to speed the iterative process and to allow the expert to answer directly using a computer.

The process began in the second week of December 2006 and the first round was concluded in the first week of January 2007.

VI.5.2 Results of the first round

The questionnaire was sent to 12 experts and 9 of them completed it[90]. It was necessary to encourage their involvement through electronic and telephone reminders. From the first round some valuable suggestions were obtained:

- Two experts felt that the questionnaire should explain clearly the differences between the installed power proposed in the coal and gas solutions and the installed power proposed in the wind solution.

  The average available power of a wind farm in Portugal is much lower than the corresponding installed power, due to wind fluctuations and intermittency. Thus, the installed power for coal or natural gas power plants may be close to the average required power but the installed power for wind farms must be much higher than the average required power. To ensure 1000 MW of average available power it will be necessary to install about 3800 MW of wind power[91] or a little more than 1000 MW of coal or natural gas power plants. The research team believed that this was an important comment and it was taken into consideration for the second questionnaire.

- One expert believed that the visual impact of the wind solution is superior to the others. However, the current environmental concerns contribute to a positive image for wind, seen as an energy source with no climatic effects. Accordingly, wind farms are associated with clean energy production and technological development and their visual impact may be perceived as positive.

[90] The researcher wish to thank the experts who generously gave their time and insights, making this study possible.
[91] Assuming an average load factor equal to 26%.

This comment was also included in the second questionnaire. The results of the first questionnaire indicate that the comparison of the visual impact of wind and thermal power plants is far from being a consensual matter. Bergmann et al. (2005) also pointed out that the aesthetics of wind projects may be contentious, with individuals feeling that wind turbines are pleasing to observe and others feeling that they take away nature's scenic beauty.

- One expert suggested the inclusion of aspects like the efficiency of the plants, the production costs or the CO_2 emissions levels.

  These aspects were already being handled in the EPM and NLEPM. In the Delphi process the research team intends to include only the qualitative aspects that may benefit from the opinion of a group of experts. In the second questionnaire this issue was clarified.

- One expert called attention to the difficulty of the comparison process, in particular when the experts were asked to pairwise compare the criteria.

  From the previous interviews with the experts of the sector this difficulty was foreseen. However, the research team believes that a group analysis, like the Delphi process may help to shed some light on the subject.

- One of the experts made some important comments on the characterisation of the wind farms. He felt that the number of wind farms and the area indicated in the description of the wind solution were exaggerated. The expert gave some examples that helped clarify this issue and sent some new photographs that he believed would represent better a modern wind farm.

  The comments were taken into consideration in the second questionnaire and the wind solution was redrawn.

- One of the experts felt that the scale used for the comparison was too long and complex.

  This question had already been raised in previous interviews. However, as the results of the Delphi process will be the input information for the AHP analysis, the scale was kept close to the Saaty proposal.

- Additional language suggestions were made by some of the experts.

  These suggestions were taken into consideration for the writing of the second questionnaire.

- One of the experts supported the view that in the future coal should be eliminated, gas could be better managed and wind farms may be seen as temporary solution for the moment.

  The researcher team felt that this opinion, although valid, would not bring new information to the process. As so, it was not included in the feedback process but it helped understanding the positions of the expert on this matter.

Each one of the questions was statistically examined using Excel Analysis Toolpack. The analysis focused mainly on the frequency distribution and on the computation of the median, quartile values and IQR. For the quartile and IQR computations it was assumed that the difference between adjacent levels was equidistant and the ordinal scale described in Table 6.2 was treated as an interval scale.

Based on studies like Hemphill et al. (2002), Scheibe et al. (2002) or Rayens and Hahn, (2000), it was assumed that an IQR of one unit was representative of a suitable level of consensus, which would not require further iteration.

Table 6.6 summarises the statistical results of the first round for question 1: pairwise comparison of the visual impact of the three solutions. The complete distribution of frequencies may be found in Annex 13.

Table 6.6- Statistical results of pairwise comparison of the visual impact of the three solutions.

	Coal-gas	**Coal-wind**	**Gas-wind**
Minimum	moderately inferior	absolutely inferior	absolutely inferior
1st quartile	equal	moderately inferior	strongly inferior
2nd quartile (median)	moderately superior	moderately superior	moderately superior
3rd quartile	moderately superior	strongly superior	moderately superior
Maximum	strongly superior	absolutely superior	strongly superior
IQR	1	3	3
Inferior range	11%	44%	44%
Equal range	22%	0%	0%
Superior range	67%	56%	56%

Consensus was achieved for the comparison of the visual impact of coal and natural gas power stations. The results revealed that more than 50% of the experts chose the same category: “moderately superior”, followed by “equal” with 22% and “moderately inferior” with 11%.

The comparison of coal and gas solutions with wind solution, demonstrated considerable less agreement. The IQR was equal to 3 and the histogram clearly shows that the responses are spread out through all categories.

Even aggregating the related categories consensus is far from being achieved. The results showed that 44% of the experts believe that the visual impact of the coal or gas solutions is superior to the visual impact of the wind solution. On the opposite about 56% of the experts think that the visual impact of the wind solution is superior to the visual impact of both coal and gas solutions.

Table 6.7 summarises the statistical results of the first round for question 2: pairwise comparison of the noise level of the three solutions. The complete distribution of frequencies may be found in Annex 14.

Table 6.7- Statistical results of pairwise comparison of the noise level of the three solutions.

	Coal-gas	**Coal-wind**	**Gas-wind**
Minimum	equal	strongly inferior	strongly inferior
1st quartile	equal	moderately inferior	moderately inferior
2nd quartile (median)	equal	moderately inferior	moderately inferior
3rd quartile	equal	moderately superior	equal
Maximum	strongly superior	moderately superior	moderately superior
IQR	0	2	1
Inferior range	0%	67%	67%
Equal range	78%	0%	11%
Superior range	22%	33%	22%

There seems to exist more consensus in what concerns the pairwise comparison of the noise level of the three solutions. High consensus was achieved for the comparison of the noise impact of coal and natural gas power stations. The results revealed that about 78% of the experts chose the category. “equal”. Only 22% of the experts chose categories of the “superior” range.

The results of the gas-wind comparison indicated less consensus, but still acceptable according to the IQR criteria. About 67% of the experts believe that the noise level of the gas solution is inferior to the wind solution, 22% think the opposite: noise level of the gas solution is superior to the wind solution and 11% chose the category “equal”.

As for the coal-wind comparison, according to the IQR criteria no agreement exists among experts. The distribution of the responses is not very different from the gas-wind comparison, with 67% also choosing categories in the “inferior” range. However, the remaining experts all chose “moderately superior”, increasing the IQR to 2.

Table 6.8 summarises the statistical results of the first round for question 3: pairwise comparison of the impact on birds and wildlife of the three solutions. The complete distribution of frequencies may be found in Annex 15.

Table 6.8- Statistical results of pairwise comparison of the impact on birds and wildlife of the three solutions.

	Coal-gas	**Coal-wind**	**Gas-wind**
Minimum	equal	absolutely inferior	absolutely inferior
1st quartile	equal	strongly inferior	moderately inferior
2nd quartile (median)	moderately superior	moderately inferior	moderately inferior
3rd quartile	moderately superior	moderately inferior	moderately inferior
Maximum	moderately superior	moderately superior	moderately superior
IQR	1	1	0
Inferior range	0%	78%	78%
Equal range	44%	0%	11%
Superior range	56%	22%	11%

The answers of the experts indicate consensus for the three pairwise comparisons. Agreement is maximum for the gas-wind comparison, with an IQR equal to zero. About 78 % of the experts believe that the impact on birds and wildlife of the gas solution is inferior to the wind solution, 11% chose the “equal” category and also 11% of the experts chose the “moderately superior” category.

The results of the coal-gas comparison revealed that the answers were confined to two categories: “equal” and “moderately superior” and the frequency values were very close to each other: 44% and 56%, respectively. This led to a higher IQR, equal to 1.

On the other hand, the comparison of the impact of coal and wind power plants on birds and wildlife indicate the opinions of experts were spread across four categories. However, 44% of the answers were in the “moderately inferior” category and a total of 78% of the answers ranged in the inferior scope. The remaining 22% of the experts think that the impact on birds and wildlife of the coal solution is “moderately superior” to the wind solution. The IQR was again equal to 1.

Table 6.9 summarises the statistical results of the first round for question 4: pairwise comparison of the social acceptance of the solutions. The complete distribution of frequencies may be found in Annex 16.

Table 6.9- Statistical results of pairwise comparison of the social acceptance of the solutions.

	Coal-gas	**Coal-wind**
Minimum	very strongly inferior	absolutely inferior
1st quartile	strongly inferior	very strongly inferior
2nd quartile (median)	moderately inferior	very strongly inferior
3rd quartile	moderately inferior	moderately inferior
Maximum	strongly superior	absolutely superior
IQR	1	2
Inferior range	78%	89%
Equal range	11%	0%
Superior range	11%	11%

Once more consensus was achieved for the comparison of the social acceptance of the coal and natural gas solutions. The distribution of the responses indicates that about 78% of the experts think that the social acceptance of the coal solution is inferior to the gas solution, 11% believes that it is the same and the remaining 11% chose the “strongly superior” category.

The results showed considerable less agreement in what concerns the coal wind comparison. Although 89% of the experts chose responses from the inferior range, the IQR was equal to 2. In fact, the distribution of the frequencies showed that the answers were spread across five categories and all of them with a frequency of response less than 34%. In the inferior range, the responses varied from “absolutely inferior” to “moderately inferior” and the IQR reflected this dispersion.

Due to a mistake, detected after sending of the questionnaires, no gas-wind comparison was conducted. This question was addressed only on the second round.

The second part of the questionnaire focused on the pairwise comparison of the social criteria. Table 6.10 summarises the statistical results of the first round. The complete distribution of frequencies may be found in Annex 17.

Table 6.10- Statistical results of pairwise comparison of the social criteria.

	VI-NL	VI-BW	VI-SA	NL-BW	NL-SA	BW-SA
Minimum	absolutely inferior	absolutely inferior	very strongly inferior	absolutely inferior	strongly inferior	strongly inferior
1st quartile	moderately inferior	strongly inferior	*strongly to moderately inferior	*strongly to moderately inferior	*strongly to moderately inferior	moderately inferior
2nd quartile (median)	moderately inferior	moderately inferior	moderately inferior	*moderately inferior to equal	*moderately inferior to equal	equal
3rd quartile	moderately inferior	moderately superior	equal	strongly superior	moderately superior	equal
Maximum	strongly superior	strongly superior	equal	strongly superior	strongly superior	moderately superior
IQR	0	3	1.25	3.25	2.25	1
Inferior range	78%	67%	67%	44.4%	44.4%	44.4%
Equal range	0%	0%	33%	11.1%	11.1%	33.4%
Superior range	22%	33%	33%	44.4%	44.4%	22.2%

* The computation of these quartile values led to non integer values.
VI-Visual impact; NL- Noise level; SA- Social acceptance; BW- Impact on birds and wildlife.

The answers of the experts indicate consensus for the pairwise comparison of visual impact with noise level. About 78% of the experts chose answers in the inferior range and the remaining 22% chose the "strongly superior" category. Consensus was also achieved for the comparison of impact on birds and wildlife and social acceptance, with an IQR equal to 1. However, the opinions of the experts were spread across more categories ranging from "strongly inferior" to "moderately superior". For all the other pairwise comparisons, the responses obtained from the experts did not lead to agreement. The IQR was higher than 1 and the frequency distribution shows that the responses were spread across the different categories and ranges, reflecting the high subjectivity of the analysis.

The third part of the questionnaire focused on the experts' willingness to pay for a reduction in pollution levels. Table 6.11 summarises the statistical results of the first round. The complete distribution of frequencies may be found in Annex 18.

The results showed no agreement in regard to this question. Most of the experts indicate that they are willing to increase their electricity bill by more than 10%. However, the distribution of the frequencies showed that the answers were spread across the four categories, with the IQR reflecting this dispersion.

Table 6.11- Statistical results of pairwise comparison of the "willingness to pay" question.

	Value
Minimum	0%
1st quartile	up to 5%
2nd quartile (median)	from 6 to 10%
3rd quartile	more than 10%
Maximum	more than 10%
IQR	2
0%	22.2%
Up to 5%	22.2%
From 6 to 10%	11.2%
More than 10%	44.4%

Table 6.12 presents a summary of the results of all the questions for the first round of the Delphi process.

Table 6.12 Summary of the results of the 1st round.

Question	IQR	Consensus
1. Visual impact		
Coal-gas	1	Yes
Coal-wind	3	No
Gas-Wind	3	No
2. Noise level		
Coal-gas	0	Yes
Coal-wind	2	No
Gas-Wind	1	Yes
3. Impact on birds and wildlife		
Coal-gas	1	Yes
Coal-wind	1	Yes
Gas-Wind	0	Yes
4. Social acceptance		
Coal-gas	1	Yes
Coal-wind	2	No
5. Social criteria		
Visual impact-noise level	0	Yes
Visual impact-birds and wildlife	3	No
Visual impact-social acceptance	1.25	No
Noise level-impact on birds and wildlife	3.25	No
Noise level-social acceptance	2.25	No
Impact on birds and wildlife-social acceptance	1	Yes
6. Increase in electricity bill	2	No

The application of the IQR equal to 1 principle produced adequate consensus for 9 of the 18 questions. These questions did not required further iteration and were not included in the second round of the questionnaire.

The results from pairwise comparison of the three solutions indicate that visual impact is the criteria with maximum disagreement among experts. As mentioned previously this is not a completely unexpected result, with the high subjectivity of this criterion easily leading to divergent opinions. The position of the experts in regard to the impact on birds and wildlife is quite consensual, and most of the expert seem to agree that the impact of coal or gas power plants is moderately inferior to the impact of wind power plants.

The pairwise comparison of the social criteria revealed increased difficulties in obtaining consensus. Once more, this is probably due to the subjectivity of the comparison and several experts reported the difficulty of the process. However, it is interesting to note that the idea that visual impact is the least important of the criteria considered seems to be consensual, corroborating the opinions collected during the first stage of semi-structured interviews.

As for the willingness to pay more for a better environment, no consensus was achieved, requiring a further Delphi round. However, comparing the results with the European Commission survey “Attitude towards energy”, it appears that expert may be willing to pay more than the average population. This is also not a surprising result, as the European Commission (2006) states “Education indeed seems essential in order to recognize and face the new energy related challenges”. Our group of experts is composed of academic staff and may be more “open-minded” with regard to clean electricity production even when cost implications are involved.

VI.5.3 Second questionnaire

The second questionnaire, sent to experts in January 2007, may be found in Annex 19. This questionnaire followed the same structure as the first one, asking the experts to assume the need to increase the available power in about 1000 MW. It included again a description of the three possible solutions. No changes were made on the characterisation of the coal and gas solutions. However, the characterisation of the wind solution was changed according to the technical comments received during the first round. Additionally, a picture from a more recent wind farm replaced the previous one.

Wind solution	
Description	180 new wind farms, with total installed capacity equal to 3800 MW.
Placement	Spread across the country, but with some particular relevance in the inland North hills.
Characteristics	Each wind farm will have between 8 and 10 turbines, about 65 m high and may occupy an area of about 25 ha (0.25 km^2).
Examples	Presently there are about 1000 turbines operating in the mainland, some examples may be seen in Marão, Açor, Barroso among many others.

The other comments, described in section VI.5.2 were also included in the new questionnaire, namely:

For the wind solution the installed power must be much higher than the average power needed. Due to wind fluctuations and intermittency, the average available power for electricity production on the wind solution is much lower than the installed power, which does not happen with either the coal or the gas solution.

The visual impact of a wind farm may be superior to the other solutions. However, some may consider this a positive impact because it represents an image of clean energy production.

The questionnaire also included a simple description of the statistical concepts used for describing the results from the first round (quartile values):

1st quartile: 25% of the responses were equal or less than the category presented.
2nd quartile (median): 50% of the responses were equal or less than the category presented.
3rd quartile: 75% of the responses were equal or less than the category presented.

Together with the additional information, questions for which round one did not produce an acceptable level of agreement were formulated in this second questionnaire. The experts' panel was presented with a summary of statistical results along with their original response to round one as feedback. Based on this information, the experts could maintain or revise their initial response. For example, question 1a) was formulated as follows:

The visual impact of the coal solution is to the wind solution.

Results from the first round:
1st quartile: "4-moderately inferior"
2nd quartile (median): "6-moderately superior"
3rd quartile: "7-very strongly superior"

Your answer to first round was:

As stated before, the ordinal scale presented to the panel members was converted to an interval scale for the statically analysis. In order to better understand the results from the first round and to make clear the assumption of equidistance between response categories, in the second round this numerical scale was presented associating to each category a rank order between 1 and 9.

This second round reduced the number of questions from the original 18 (in the first round) to 10. However, the complexity of the process was increased because the experts had now to analyse the alterations and comments made, along with the statistical results of the first round. To facilitate the experts' job and to reduce the answering time, the second questionnaire distinguished this new information from the remaining text. The experts could easily recognise the new information, because it was written in a different colour and the statistical results were presented in boxes next to the respective question.

The process began in the second week of January 2007 and the first round was concluded in the last week of February 2007.

VI.5.4 Results of the second round

The questionnaire was sent to the 9 experts that previously answered the first questionnaire and all of them completed it. Once more, it was necessary to encourage involvement through electronic and telephone reminders. The process lasted for a longer period than the first round, which may be associated with the complexity of the analysis and some weariness of the participants.

During the second round two additional comments were received, both related to visual impact. These experts believed that the interpretation of visual impact was not straightforward. Some experts might answer on the basis of the direct impact of wind power plants on the landscape; and others might be influenced by the public opinion's positive image of wind power.

Similarly to the 1st round, each one of the questions was statistically examined using Excel AnalysisToolpack. Along with statistical measures, the percentage change of the responses was also computed to evaluate the stability of the process. Following Schebe et al. (2002), a 15% change level or less indicated stability.

Table 6.13 summarises the statistical results of the second round for question 1: pairwise comparison of the visual impact of coal and wind solutions and comparison of the visual impact of gas and wind solutions. The complete distribution of frequencies and the stability measurement computations may be found in Annex 20.

Table 6.13- Statistical results of pairwise comparison of the visual impact of the solutions (2nd round).

	Coal-wind	Gas-wind
Minimum	1. absolutely inferior	1. absolutely inferior
1st quartile	4. moderately inferior	3. moderately inferior
2nd quartile (median)	6. moderately superior	6. moderately superior
3rd quartile	6. moderately superior	6. moderately superior
Maximum	7. strongly superior	6. moderately superior
IQR	2	3
Inferior range	44%	44%
Equal range	0%	0%
Superior range	56%	56%
Change	22%	11%

Once more consensus was not achieved for the comparison of the visual impact of wind plants with either coal or gas power plants. Although achieving a reduction of the IQR for the coal-wind comparison, the experts are still divided about this subject. For gas-wind comparison, the IQR remains unchanged and stability seems to have been reached, probably due to the resistance to opinion change. For coal-wind comparison, the values indicate no stability, however only a few changes of category in the superior range were obtained showing a tendency to centralise in less extreme positions.

Table 6.14 summarises the statistical results of the second round for question 2: pairwise comparison of the noise level of coal and wind solutions. The complete distribution of frequencies and the stability measurement computations may be found in Annex 21.

Table 6.14- Statistical results of pairwise comparison of the noise level of the solutions (2nd round).

	Coal-wind
Minimum	3. strongly inferior
1st quartile	4. moderately inferior
2nd quartile (median)	4. moderately inferior
3rd quartile	4. moderately superior
Maximum	4. moderately superior
IQR	2
Inferior range	67%
Equal range	0%
Superior range	33%
Change	11%

The IQR range remains equal to 2 and frequency distribution indicates that most of the experts still concentrate on the inferior range with minor changes on the chosen category. These small changes indicate that the distribution may be considered stable.

Table 6.15 summarises the statistical results of the first round for question 4: pairwise comparison of the social acceptance of coal and wind solutions and pairwise comparison of the social acceptance of gas and wind solutions. The complete distribution of frequencies and the stability measurement computations may be found in Annex 22.

Table 6.15- Statistical results of pairwise comparison of the social acceptance of the solutions (2nd round).

	Coal-wind	**Gas-wind**
Minimum	1. absolutely inferior	3. strongly inferior
1st quartile	1. absolutely inferior	3. strongly inferior
2nd quartile (median)	2. very strongly inferior	4. moderately inferior
3rd quartile	3. strongly inferior	4. moderately inferior
Maximum	4. moderately inferior	4. moderately inferior
IQR	2	1
Inferior range	100%	100%
Equal range	0%	0%
Superior range	0%	0%
Change	22%	--

High consensus was achieved in the comparison of the social acceptance of natural gas and wind solutions. The distribution of the responses indicates that all the experts think that the social acceptance of the gas solution is inferior to the wind solution, 56% believe that it is "moderately inferior" and the remaining 44% chose the "strongly inferior" category.

The coal-wind comparison, although aggregating all the answers in the inferior range, still presents an IQR equal to 2. The distribution of frequencies showed that the answers were spread across the four inferior categories and the IQR reflected this dispersion. Once more, stability seems not to be reached. However, also in this case only minor changes of category in the inferior range were observed.

The second part of the questionnaire focused on the pairwise comparison of the social criteria. Table 6.16 summarises the statistical results of the first round. The complete distribution of frequencies and the stability measurement computations may be found in Annex 23.

Table 6.16- Statistical results of pairwise comparison of the social criteria (2nd round).

	VI-BW	VI-SA	NL-BW	NL-SA
Minimum	2. very strongly inferior	2. very strongly inferior	2. very strongly inferior	3. strongly inferior
1st quartile	3. strongly inferior	3. strongly inferior	3.75 strongly to moderately inferior*	3. strongly inferior
2nd quartile (median)	4. moderately inferior	4. moderately inferior	4.5 moderately inferior to equal*	4. moderately inferior
3rd quartile	6. moderately superior	4. moderately inferior	6. moderately superior	6. moderately superior
Maximum	7. strongly superior	5. equal	7. strongly superior	7. strongly superior
IQR	3	1	2.25	3
Inferior range	56%	78%	44.4%	56%
Equal range	0%	22%	11.2%	11%
Superior range	44%	0%	44.4%	33%
Change	11%	11%	33%	11%

* The computation of these quartile values led to non integer values.
VI-Visual impact; NL- Noise level; SA- Social acceptance; BW- Impact on birds and wildlife.

The answers of the experts indicate consensus for the pairwise comparison of visual with social acceptance. About 78% of the experts chose answers in the inferior range and the remaining 22% chose the “equal” category.

For the remaining questions IQR remains high. With the exception of the pairwise comparison of noise level with the impact on birds and wildlife, stability seems to have been reached with an unconsensual distribution of opinions. The noise level - impact on birds and wildlife comparison presented a tendency to centralise more extreme solutions, which was reflected on the high percentage of change.

The third part of the questionnaire focused on the experts’ willingness to contribute financially to a decrease in pollution levels. Table 6.17 summarises the statistical results of the second round. The complete distribution of frequencies and the stability measurement computations may be found in Annex 24.

The results showed again no agreement in relation to this question. The results indicates that about 45% of the experts are not willing to increase their electricity bill or only accept a 5% increase to contribute to a decrease in pollution levels. However, the most frequently chosen category was “more than 10%”, once more showing the wide range of opinions on this matter. The distribution of frequencies showed that the answers were spread across the four categories, with the IQR reflecting this dispersion. Stability was reached with no expert changing opinion from one round to the other.

Table 6.17- Statistical results of pairwise comparison of the "willingness to pay" question (2nd round).

	Value
Minimum	0%
1st quartile	up to 5%
2nd quartile (median)	from 6 to 10%
3rd quartile	more than 10%
Maximum	more than 10%
IQR	2
0%	22.2%
Up to 5%	22.2%
From 6 to 10%	11.2%
More than 10%	44.4%
Change	0%

Table 6.18 presents a summary of the results of all the questions for the second round of the Delphi process.

Table 6.18- Summary of the results of the 2nd round.

Question	IQR	Consensus	Stability	Relaxed consensus[1]
1. Visual impact				
Coal-wind	2	No	No	No
Gas-Wind	3	No	Yes	No
2. Noise level				
Coal-wind	2	No	Yes	Yes
3. Social acceptance				
Coal-wind	2	No	No	Yes
Gas-wind	1	Yes	--	Yes
5. Social criteria				
Visual impact-birds and wildlife	3	No	Yes	No
Visual impact-social acceptance	1	Yes	Yes	Yes
Noise level-impact on birds and wildlife	2,25	No	No	No
Noise level-social acceptance	3	No	Yes	No
6. Increase in electricity bill	2	No	Yes	No

[1] Assuming consensus for questions with IQR=2 and more than 60% of the answers in one range (inferior, equal or superior).

For three questions stability was not achieved. For all of them there was an obvious tendency to centralise more extreme positions, however this lack of stability was only due to minor changes of category with no changes in range occurring. Most of the questions of the second round achieved stability but not consensus, meaning that the experts opinions are wide-ranging and some resistance exists on moving to centralisation. Even when the relaxed consensus was assumed, only four of the 10 questions could be considered consensual.

It is not easy to reach consensus for the issues in question and it is the researcher's belief that due to the complexity and subjectivity of the theme a third iteration would be unlikely to bring new valuable information to the model. It was however possible to achieve consensus in 12 of the 19 questions. It is also important to keep in mind that the group of experts consisted of only nine persons, and as so extreme answers or changes on even just one or two expert responses can have important effects on the statistical results and may influence the decision of consensus or stability[92]. For larger groups, if there is no agreement Hobbs and Meier's (2003) suggestion may be followed, of using cluster analysis or factor analysis to analyse the positions of various stakeholders.

As Hobbs and Meier (2003) state, one should expect significant differences among individuals concerning their values on energy planning alternatives. These authors argue that consensus may be very difficult or even unachievable, yet often the search for consensus will establish at least some common ground. Based on this, it seemed reasonable to proceed with the study, applying the results obtained to an exploratory model to develop a methodology to incorporate non quantitative aspects in the electric planning process. This group of experts should be seen as a pilot group; nevertheless even if a broader group of social agents is consulted difficulties and divergence of opinions on the subject are always to be expected. On a more general level, the study would greatly benefit from increasing the number of experts consulted and from the inclusion of other social groups. This would bring more views to the discussion and would make the statistical analysis less sensitive to individual extreme positions. The involvement of central planners in the Delphi study would bring considerable advantages to the process, contributing for the definition of the social criteria more relevant for the Portuguese society and increasing the number of experts participating in the study.

VI.6 Determination of weights for the electricity generation options

This phase of the research combines the information obtained from the Delphi process with AHP, in order to convert pairwise comparison of the elements of the hierarchical structure in an overall social index, allowing for the ranking of the alternative ways of meeting the demand for electricity. The pairwise comparisons of each expert were used as input for the SuperDecisions software using the scale presented in Table 6.2 associated with a numerical

[92] For example for the pairwise comparison of the visual impact of coal and wind solutions if two of the experts holding position "moderately inferior" would change their position to "equal" the IQR would be equal to one and consensus could be assumed.

score as presented in Table 6.19.

Table 6.19- Scale preferences with numerical score

Score	Pairwise evaluation
9	Absolutely superior
7	Very strongly superior
5	Strongly superior
3	Moderately superior
1	Equal
1/3, 1/7, 1/5, 1/3	Reciprocal values

The consistency of each comparison matrix was tested and the relative weights of the elements on each level were computed for each expert.

As the consistency ratio is above 10% for some of the resulting matrixes, only the relative scores of matrixes passing the consistency test were included in the aggregation process. Thus:

- the relative weights of the alternatives with respect to noise are based on 8 experts' points of view;
- the relative weights of the alternatives with respect to impact on birds and wildlife and social acceptance aggregate the opinions of 5 experts; and
- for visual impact only 4 experts provided judgments passing the consistency test.
- The relative weights of the four criteria aggregate opinions from 6 experts.

The group view was represented by the aggregation of each individual's resulting priorities. Forman and Peniwati (1998) argued that although this aggregation may be computed using either a geometric or arithmetic mean, the geometric mean is more consistent with the meaning of both judgments and priorities in AHP. In fact, studies such as Hon et al. (2005), Wu et al. (2007) or Banuls and Salmeron (2006), resource also to the the geometric mean method. Tables 6.20 and 6.21 give the aggregated comparison matrix for the criteria and for the alternatives under each criterion using the geometric mean for the aggregation of the experts' opinions into the final judgement [93].

The priority vector ranking of criteria with respect to the general goal indicates that social acceptance ranked first followed by impact on birds and wildlife. All these criteria reflect negative aspects for society. For the sake of the consistency of the analysis, social

[93] Values obtained with the software package Super Decisions.

acceptance criterion was computed as the reciprocal corresponding to “social rejection”.

Table 6.20 - Aggregated unweighted comparison matrix for the criteria.

Criteria	Priority ranking
Impact on birds	0.240
Noise impact	0.186
Social acceptance	0.284
Visual impact	0.110

Table 6.21- Aggregated unweighted comparison matrix for the alternatives under each criterion.

Solution \ Criteria	Impact on birds	Noise impact	Social acceptance	Visual impact
Coal	0.248	0.218	0.716	0.345
Gas	0.199	0.186	0.202	0.219
Wind	0.385	0.542	0.075	0.275

According to the group members’ assessments the wind solution ranked first with respect to the impact on birds and wildlife and to the noise impact. Meaning that of the three solutions, wind is the one with strongest negative impacts on birds and wildlife and on noise level. For the other two criteria (visual impact and social acceptance) coal ranked first, meaning that of all the three solutions, coal is the one with strongest negative impacts on visual perception and social acceptance.

Combining the relative weights of the elements at each level of the hierarchical structure, the final scoring of the electricity generation options against the overall social objective is obtained. Table 6.22 synthesises the overall normalised priorities for the three solutions.

Table 6.22- Aggregated score for the overall social impact of the electricity generation options.

Solution	Social impact
Coal	0.455
Wind	0.326
Gas	0.219

According to the results of the group judgment, coal solution presents the highest social impact followed by wind solution. Gas solution seems to be the one ranking better from the global social point of view. The high weight of the social acceptance criterion combined with the low social acceptance of coal comparatively to gas or wind solutions, led to a score translating high negative social impact for the coal solution. Gas solution ranked in last for all but social acceptance criteria, resulting in a low overall social impact for this option.

VI.7 Discussion of the results

The prioritisation process of the different electricity generation options based on their social impact is a complex problem that involves subjective value judgments. An evaluation method combining AHP and Delphi method was adopted. The hierarchical structure enabled the relevant social criteria to be isolated, allowing the clear evaluation of each alternative against each criterion. The Delphi panel of experts allocated scores to each level of the hierarchical structure with the final aim of obtaining an overall social index of the alternatives.

The experts revealed some difficulties in translating their opinions using a scale for comparing alternatives and on the generalisation of their opinions on each of the generation alternatives and criteria. The comparison of the wind solution with both gas and coal solutions with respect to their visual impact, was particularly difficult due not only to the subjectivity of the subject but also due to the different interpretations of the concept: some of experts based their answers on direct impact of wind turbines on the landscape and others associated wind farms with clean energy production and perceived the visual impact as positive. It was also not possible to achieve consensus when assessing the importance of some of the criteria to the overall social ranking of the alternatives. Even in the second round, few changes occurred and most of the experts showed resistance to moving to centralisation.

After collecting the data, the consistency of the responses of each expert was analysed. Due to the complexity of the subject studies like Linares and Romero (2002), assumed that a 20% CR would be acceptable when assessing the importance of several criteria to the energy planning problem in Spain. For the present study, Saaty proposed value for the CR was imposed and the minimum CR was set equal to 0.1 (Kablan, 2004). Only the experts' matrixes complying with this condition were included in the final aggregation.

It should be highlighted that the difficulty on reaching consensus and consistent results is not a completely unexpected result. As Hobbs and Meier (2003) pointed out, trading off attributes often involves conflicting, strongly held values, leading to unstable weights.

Based on their experience, the authors state that many energy planners and decision makers are uncomfortable with tradeoff questions, therefore it is important to check consistency. Also, the broad diversity of interests and values of the decision makers makes consensus very difficult to achieve in the energy planning process.

Regardless of these difficulties, the research succeeded in proposing and testing a framework to deal with the non quantitative aspects of the energy planning process. It was possible to select and encourage a group of experts to participate on the research as a pilot group building an exploratory model to integrate their individual opinions. From the information collected an overall social index was assigned to each electricity generation option.

According to AHP results, the rank of gas solution was the first in the order of priority, most probably because it represents a compromise solution. It is seen as an electricity generation solution with low environmental problems, which increases its social acceptance over coal. It has also reduced impacts on wildlife specially when compared to wind power, and lower visual and noise impact than both other alternatives. Coal ranks in last, mainly due to the reduced social acceptance of this alternative. The impact on birds and wildlife and the noise impact are the most severe effects reported for wind power comparatively to both coal and gas solutions. The next section of this chapter combines this social evaluation with the environmental and economic evaluations of the the NLEPM described in Chapter V, resulting in a new Integrated Electricity Planning Model (IEPM).

VI.8 Incorporating the social index into the electricity planning model

Figure 6.5 outlines the IEPM, including the input information, output results and the aggregation of information.

The input information for the problem includes:

- the criteria identified and assumed to be relevant for the evaluation process;
- the acceptable plans drawn from the NLEPM and characterised by the cost, CO_2 levels, external energy dependency and associated capacity expansion;

➢ the basis for the Delphi survey: panel of experts and questionnaires.

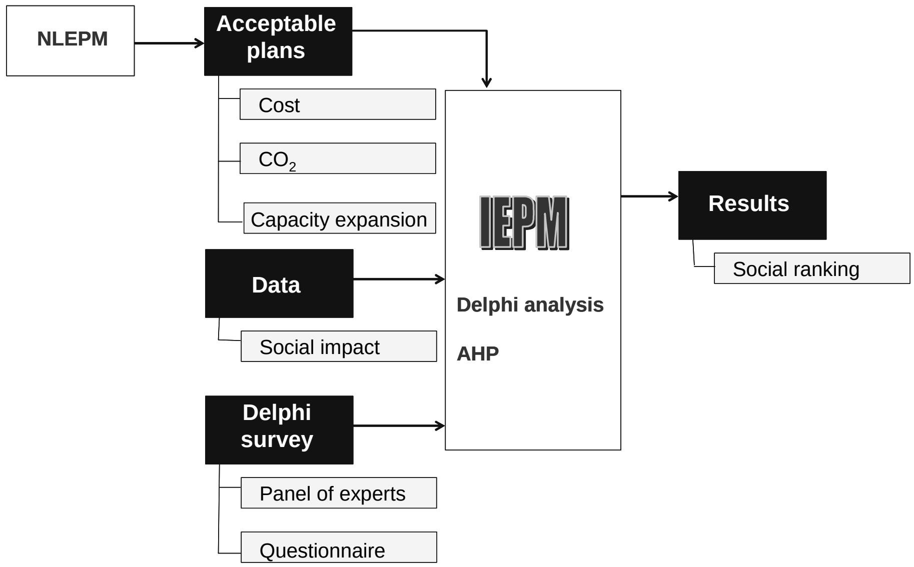

Figure 6.5- Schematic resume of the IEPM.

AHP and Delphi techniques are used for the analysis of the input to the model and the final result is a social ranking for each electricity plan. In order to obtain a final ranking of the available solutions, the overall social scores of the three alternatives must be aggregated by means of a mathematical algorithm. The aim is to get a final index for each possible plan, combining more than one of the available electricity generation technologies. For this the weights were aggregated using an additive function.

This additive function assumes that the weights assigned to each electricity generation option are constants and satisfy the additive independence, i.e. these weights do not depend on the relative levels of each option. This additive value model offers a simple way of evaluating multiattribute alternatives. This simplicity makes it widely used in energy planning and policy, as described by Hobbs and Meier (2003).

Equation 6.6 presents the computation of the average social index (ASI) for each electricity plan derived from the NLEPM, depending on the installed power of each electricity generation option and on the weights derived from the AHP.

$$\mathrm{ASI} = \frac{\sum_t (\mathrm{IP}_{4t} + \mathrm{IP}_{1t})\mathrm{W}_{coal} + \sum_t (\mathrm{IP}_{5t} + \mathrm{IP}_{2t})\mathrm{W}_{gas} + \sum_t (\mathrm{IP}_{9t} + \mathrm{IP}_{3t})\mathrm{W}_{wind}}{\sum_t (\mathrm{IP}_{4t} + \mathrm{IP}_{1t} + \mathrm{IP}_{5t} + \mathrm{IP}_{2t} + \mathrm{IP}_{9t} + \mathrm{IP}_{3t})} \tag{6.6}$$

Where W_{coal}, W_{gas}, W_{wind}, represent the overall normalised weights for the coal, gas and wind solutions, described in table 6.22.

From the NLEPM resulted an emission-cost tradeoff curve. This curve is described by discrete points, each one representing an optimal strategy for the electricity sector in the next 10 years. However, as mentioned before the non optimal solutions may not be easy to discard. Decision makers may not be willing to reject some plan that is not significantly worse than the mathematical optimal and may be more interesting from the social point of view.

The inclusion of the social index on the electricity planning process acknowledges the existence of alternative electricity plans drawn directly from the optimisation process and additional plans that although not optimal from the mathematical point of view may be socially more interesting. To illustrate the process a set of possible plans were chosen, taking into consideration that the average annual CO_2 level for the power plants included in the model could not exceed 20 Mt (Kyoto protocol target): the Solutions described in Table 5.16 were used, representing plans not necessarily belonging to the Pareto front.

Table 6.23 presents again these plans along with the respective computed ASI.

Table 6.23- Possible electricity plans obtained from NLEPM.

		NLS4	**NLS4.1**	**NLS5**	**NL5.1**
	Comments	Pareto solution	$IP_{3a,2012} \geq 6500$	Pareto solution	$IP_{3a,2012} \geq 6500$
Total installed power (MW)	Coal (new)		2400		600
	Coal (existing)	1820	1820	1820	1820
	Natural gas (new)	5040	1860	5110	3720
	Natural gas (existing)	2916	2916	2916	2916
	Wind (new)	3225	6514	3225	6500
	Wind (existing)	1515	1515	1515	1515
	Large hydro	5805	5805	5805	5805
	NWSRP	3245	3245	3245	3245
	Total	23566	26075	23636	26121
Share of RES (%)		39	45	39	46
External dependency (%)		65	58	65	57
Cost (€/MWh)		33.627	34.961	34.365	36.950
CO_2 (ton/MWh)		0.379	0.379	0.332	0.332
ASI		**0.284**	**0.328**	**0.284**	**0.303**

Some factors condition the range of ASI[94] values obtained:

- The renewable constraint imposes a minimum amount of wind power in the system. Even for plans with lower installed wind power, this technology still represents about 20% of the total installed power in the system. For large wind scenarios (solutions NLS4.1 and NLS5.1) this share reaches a little more than 30%, meaning that the maximum difference between plans is only about 10% in what concerns installed wind capacity.

- The system already possesses substantial coal and gas power capacity, once more diluting the effect of new entrances. For example, for NLS4 and NLS5 although not any new coal power plants are projected, the installed coal share still represents almost 8% of the total installed power in the system.

- The Kyoto protocol, imposes maximum CO_2 levels. Extreme solutions characterised by high coal shares and that might represent plans with higher ASI are not included in the analysis. Likewise, plans with very low CO_2 levels (and lower ASI) represent a high cost increase and may be view as academic due to the exclusive reliance on new CCGT, hydro and SRP (NLS7 or NLS8 describe din Table 5.15 for example).

- The differences on the ASI seem to be mainly influenced by the installed power of coal power plants.

- Plan NLS4.1 presents the worst outcome from society's point of view, because of the high values for the installed wind and coal power and lower installed power of gas plants.

- Plans NLS4 and NLS5 present the lower ASI due to the reduced share of coal and high share of gas power plants.

Combining the results of the optimisation procedures with the data collected in the participative process, it will be possible to present the decision maker with a selected

[94] The ASI ranges between 0.280 (NLS7) and 0.357 (NLS0) for the plans presented in Table 5.15.

number of feasible electricity generation plans characterised by the mix of technologies, total cost, total CO_2 emissions, ASI and external dependency. For example, with respect to the plans described in Table 6.23, the results reveal that it will be possible to achieve average CO_2 emissions equal to 20 Mton/year at a minimal cost of 33.6 €/MWh, investing mainly on new natural gas power plants (Solution NLS4). As natural gas is a socially well accepted solution, the social impact of this strategy should be low[95] but the external dependency of the electricity generation sector will remain high. If the decision maker is willing to increase cost by about 4% (Solution NLS4.1), it will be possible to keep CO_2 emissions at the same level and the external dependency of the electricity production sector may be reduced by 7%. Also, a more equilibrated mix between coal and natural gas may be achieved resulting in considerable advantages from the security of supply point of view. However, as this strategy requires less natural gas power plants and additional investments in new coal and wind power plants, the ASI of NLS4.1 is higher than the value obtained for the NLS4 solution.

This analysis allows the decision maker to recognise the differences between possible electricity generation alternatives and foresee their estimated impacts. The final selection of an electricity strategy for the future depends on the priority that the decision maker chooses to assign to each one of the objectives considered.

VI.9 Conclusions

The complex nature of different generation options has been highlighted by this analysis. The combination of Delphi and AHP methodologies was used to illustrate a possible process of social evaluation of the future electricity plans assigning a numerical scale to each individual option. The process started with the identification of the relevant criteria and the selection of the experts that participated in the process as a pilot group. The global objective of the hierarchy process was to obtain a ranking of the three generation options (alternatives) translating social attributes into an ASI based on the views of a group of experts. Economic and emission criteria were already addressed with the optimisation model. Optimal and close to optimal solutions drawn from the NLEPM were then analysed.

[95] In what concerns the four social criteria analysed: impact on birds and wild life, visual impact, noise level and social acceptance.

In general, the results of the Delphi analysis revealed lack of consensus among experts in some questions. In particular, the visual impact of the wind solution comparatively to both the coal and the gas solutions seems to be the least consensual aspect. It was also difficult or even impossible, to reach consensus regarding the pairwise comparison of the importance of all the criteria. However, the results seem to be stable with only few response changes between the first and second round.

The AHP results also revealed some inconsistency, leading to the reduction on the number of responses considered valid for each pairwise comparison. A careful analysis of the results allowed for the computation of a numerical index characterising each generation option from the social point of view. According to the aggregated information collected from the experts, the best solution from the social point of view would be NLS4 or NLS5 due to the reduced share of coal and high share of gas power plants. Nevertheless, the results must be approached with caution because they depend on the experts consulted and on their individual judgments. If considering the individual preferences of each expert, the rank of the options would be different from the one obtained with the aggregated weight analysis. For example, for experts with a strong wind preference the solutions with lower ASI would be NLS4.1 and NLS5.1.

The research included only three generation options. The results led to a high negative social impact assigned to the coal solution, mainly due to low social acceptance. However, the energy markets are dynamic and the social perception of each technology is highly influenced by strong stakeholder groups and in particular media (Shackley et al., 2005). The new clean coal technologies and the prices development may easily change this general opinion. Likewise, the spreading of wind power plants may demonstrate that the social impacts of this technology are more or less important than these experts assumed.

The combination of social, environmental and economic evaluations will benefit the energy plan formulation, ensuring the robustness of the process and leading to a defensible choice aimed at reducing conflict. A mixed model of subjectivity and objectivity is ultimately needed for the best ranking tool (Nigim et al., 2004). The experiment conducted revealed that the process is long and difficult. Regardless of these implementation difficulties, based on the opinions of a group of experts, the model recognises the overall social impact of each electricity generation option, identifies their major reported impacts and assesses the relative importance of these impacts for the society.

VI.9.1 Limitations and research requirements

The application of the model was presented through a pilot experiment, but considerable research is still required.

In particular, the research must go beyond the pilot experiment by the inclusion of possible additional social criteria and by increasing the number of participants in the questionnaire phase. The identification and inclusion of participants representing different stakeholder groups may add new information to the process. A broader analysis could contribute to the identification of the major sources of concern for each stakeholder group, giving also further insight into aspects of acceptance and critical factors for success in developing electricity generation projects and strategic plans.

The research revealed that the responses are some times inconsistent and consensus among experts is difficult to achieve. The process may be complemented with interviews and by presenting the feasible plans to the experts. This may help clarify experts' judgments and contribute to obtaining additional insights on the electricity generation technologies in the context of the overall electricity plan.

CHAPTER VII

INTEGRATED ELECTRICITY PLANNING MODEL

This chapter presents the Integrated Electricity Planning Model, describing the main steps involved in the proposed methodology for the formulation of electricity plans.

VII.1 Introduction

The research presented in the previous chapters strongly emphasised the need to address social aspects along with the economic, environmental, legal and technical factors. This calls for the inclusion of qualitative aspects and involvement of individuals either representing experts or stakeholders. This of course adds additional complexity to the traditional models but it is also essential to support the energy decision process based on more defensible assumptions.

A structured decision making process should include the definition of objectives and measures of performance, the identification and evaluation of alternatives, and offer choices based on a clear understanding of uncertainties and trade-offs (Failing et al., 2007). In general, this structured decision making process is comprised of the following steps:

- The identification and structuring of the problem. In this phase the decision maker clarifies the problems and the main goals of the decision process.

- The identification and characterisation of the alternatives. The information necessary for making an informed decision is gathered together and considered.

- The definition of performance measures. Based on the objectives considered the evaluation criteria are established.

- The evaluation of the alternatives. Each alternative is evaluated based on predictions of how it will affect the performance measures.

- The selection of the alternatives. This step involves addressing trade-offs among competing objectives. At the end a preferred option is selected by the decision maker for implementation.

From the work presented in this thesis, a structured decision making process for the electricity power planning problem may now be outlined, combining different techniques and involving several integrated steps. The Integrated Electricity Planning Model (IEPM) highlights the importance of the specific technical analysis of each electricity system but recognises also that energy decisions should be guided by a context that reflects economic, environmental and social concerns. This distinct and comprehensive referential framework is a useful instrument to distinguish and evaluate different energy strategies and plans, thereby contributing for facilitating explicit discussion and informed decision making,

VII.2 Integrated Electricity Planning Model

Based on the models presented, the main steps of the proposed multidimensional electricity planning process are summarised in Figure 7.1 and applied in particular to Portugal.

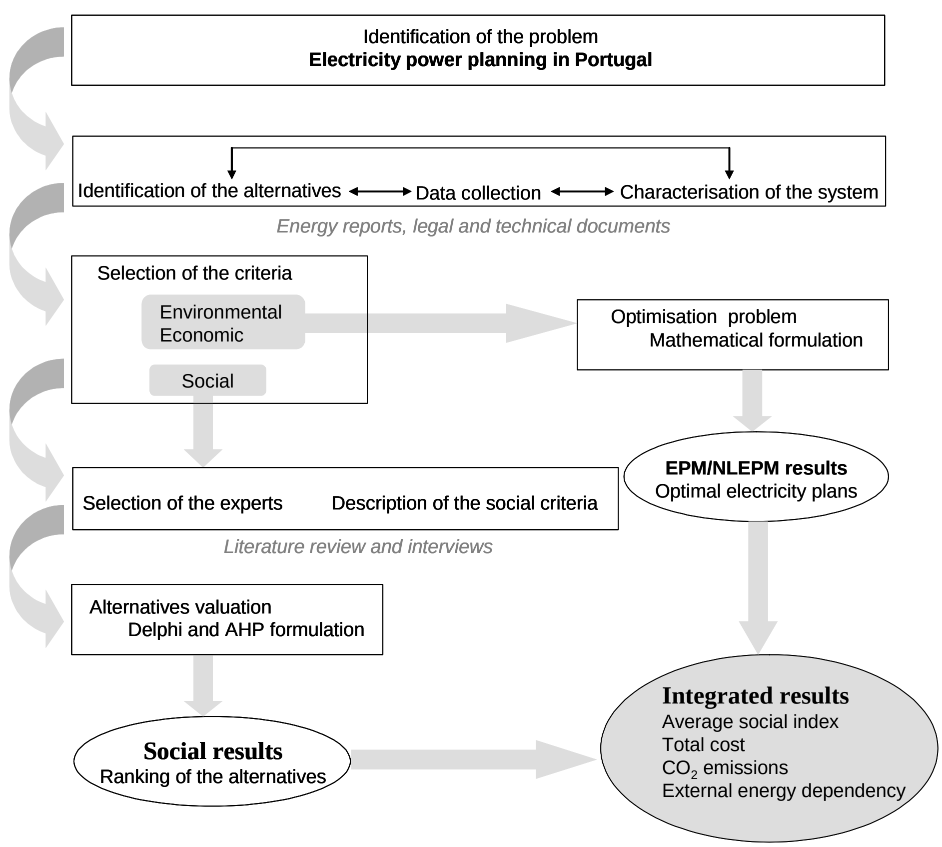

Figure 7.1- Multidimensional participatory model for electricity planning.

***Step 1*:** Identification of the problem:

- This research focused in particular on the case of electricity power planning in Portugal. The analysis of the energy system in Portugal indicated that the electricity generation sector is the largest consumer of primary energy, relying mainly on imported energy sources. In addition, the high level of greenhouse gas emissions

(GHG) of the sector makes it an important target for CO_2 mitigation.

- The main goal was to identify the optimal electricity power plan for a ten year planning period (2008-2017) in Portugal, based on the established objectives and on the performance measures.

***Step 2*:** Identification and characterisation of the alternatives:

- This step involves the characterisation of the existing electricity system and the identification of possible electricity generation alternatives to be added in the future. The power plants were characterised along with the demand and all relevant characteristics of the Portuguese electricity system. Besides collecting information on each individual technology, the operating conditions of the entire system were also considered.

- The characterisation of the power plants included the analysis of their investment and operating costs, CO_2 emissions and characteristic curve of operation. Aspects like the expected hydro inflows, reserve levels for the hydro storage power plants, security of the system and legal requirements were also taken into account.

- The electricity generation alternatives were explicitly defined and the electricity plans or strategies for the future are based on a mix of these technologies. These plans are thus implicitly defined under the mathematical formulation of the model.

***Step 3*:** Selection of the criteria taken into consideration in the decision process.

- The literature review on sustainable energy planning demonstrates the need to integrate financial, environmental and social dimensions into the decision process. The economic and environmental impacts (pollutant emissions) can be described according to quantitative scales, although measured in different units. Most of the other impacts can not be described with values directly derived from the technical characteristics of the electricity system. The participation of the social players becomes then essential.

- The main criteria considered for the evaluation problem were: total present cost of the system for the entire planning period, total CO_2 emissions released during the planning period, the Average Social Index (ASI) and external energy dependency.

***Step 4*:** Mathematical formulation of the economic and environmental objectives.

- This step involves the evaluation of all relevant costs and pollutant emissions. Investment, O&M, fuel and emissions costs must be evaluated based on the characteristics of each power plant and on their operating regime in each particular electricity system. The environmental objective may involve a variety of aspects such as, SO_2, NO_x, Greenhouse Gas, water consumption and temperature changes or industrial residuals. For this particular case, CO_2 was used as a proxy for the environmental dimension of the problem.

- The Portuguese electricity system was described for the ten year planning period using mathematical functions, to specify the objectives and the constraints. The process resulted in two optimisation problems, corresponding to the Electricity Planning Model (EPM) and the Non-Linear Electricity Planning Model (NLEPM).

Step 5: Computation of the quantitative results, describing possible electricity plans.

- The relative merit of each plan implicitly defined in the optimisation models is determined on the basis of its performance on the cost and CO_2 criteria.

- The final result of this step is the description of possible electricity plans obtained according to quantitative criteria, which are optimal from both financial and environmental points of view. The external dependency of the electricity sector is also computed for each plan. In this work, these results correspond to the output of the NLEPM or the EPM.

***Step 6*:** Development of a methodology for addressing the social dimension of the decision process.

- This step involves selecting and engaging experts and/or stakeholders in the process. The careful selection of experts and their motivation for the research area are fundamental to ensure the success of this process. For this particular research, university staff was selected as a pilot group.

- The process comprises of defining and characterising the social criteria to be included in the analysis. In this study four sub-criteria were used, but in a broader study other criteria may be important, e.g. employment, impact on local communities or health (see for example Gamboa and Munda (2007) and Cavallaro and Ciraolo (2005)). The aim is to present a set of attributes characterising each electricity generation option that may help to rank these from a social perspective.

Step 7**:** Evaluation of the possible electricity generating alternatives in the context of social criteria.

- This step involves the integration of both Delphi and Analytic Hierarchy Process (AHP) methodologies for ranking the alternative. The process is based on the pairwise comparison of the alternatives and of the criteria previously defined. For this particular study, a questionnaire was written presenting the departing situation of the Portuguese electricity system and proposing different solutions for a marginal increase of the available power. The questionnaire was sent to experts in a two round Delphi process. The results of the questionnaire were analysed using AHP.

Step 8**:** Computation of the social impact for each electricity generation technology.

- Following analysis of the questionnaire, the electricity generation technologies may be ranked, and a social impact value may be assigned to each of these technologies.

Step 9**:** Integrated evaluation of the electricity plans

- Electricity plans, considered optimal (or close to optimal) from both a economic and environmental point of view, are now evaluated from a social point view. Each generation mix is weighted with the appropriate social index of each technology, resulting in the average social index (ASI). For this research, additive independence was assumed and weights were aggregated using a linear additive function.

From the application of the outlined process, in respect of a selected number of feasible electricity generation plans the decision maker is given cost, total CO_2, ASI and external dependency of the electricity generation sector, from which a final decision may be made.

CHAPTER VIII

CONCLUSIONS AND FUTURE WORK

This chapter summarises the main conclusions of the thesis, research contributions and opportunities for future research.

VIII.1 Conclusions

Three major challenges guide energy policy at the European and Portuguese levels: sustainability, security of supply and competitiveness. Meeting these policy objectives calls for profound changes in the electricity power sector, through the implementation of policies designed to address the link between energy use and environmental deterioration. Issues such as improving energy security, local economic development, energy prices and improvement in energy efficiency are key priorities in European policy for the energy sector. The rising fuel prices and a growing concern for the environment have prompted interest in using renewable energy sources (RES). The move towards renewable energy technologies is strongly stressed in the European and Portuguese policies. Particularly remarkable has been the development of wind power and its expected role as an electricity generation technology.

According to Rede Eléctrica Nacional forecasts (REN, 2005), electricity demand in Portugal is expected to grow from 52764 GWh in 2006 by a yearly figure close to 4.4% to 82070 GWh in 2016. The present electricity system is mainly based on coal, CCGT and hydro power. The REN's (2005) study for the electricity power sector indicates that for the next ten years, although all the energy sources are expected to grow, the move towards renewable energy sources will be the most significant change in the system. This will be mainly due to the rapid growth of the wind power sector supported essentially by the government's policy on renewable energy.

Electricity power planning is, using the definition of Hobbs (1995) "the selection of power generation and energy efficiency resources to meet customer demands for electricity over a multi-decade time horizon". The changes in the electricity sector along with the need for sustainable development required traditional electricity planning to expand beyond pure financial analysis and even beyond direct environmental impact analysis. The increasing use of RES in electricity systems adds additional considerations to the traditional planning models, in particular the need to take into account: (i) their frequent priority access to the grid system; (ii) the impacts that technologies of variable output, such as wind energy can have on the overall operation of the electricity system and (iii) the public attitude towards these technologies. In addition, the central electricity planning process based on a single decision maker is no longer acceptable and the importance of examining tradeoffs among objectives is now well recognised. Considering the three dimensions of sustainable development has gradually increased the importance of the social aspect in the decision process. The energy planner has now the task of designing electricity strategies for the future with the view of enhancing the financial performance of the sector while simultaneously addressing environmental and social concerns. Thus, the planners must deal, not only with variables that may be quantified and simulated but also with the social impact assessment.

The electricity planning process has been addressed by a large number of authors, proposing different approaches and methods to solve these problems. Most of these approaches include diverse multicriteria tools, expressing each criteria in its own units, or involving some kind of cost benefit analysis, in which environmental criteria are expressed in economic terms. The process frequently requires the planner to work with quantitative and qualitative information. However, continuous models like the ones from the EFOM or MARKAL family, focus mainly on the cost and economic dimensions of the problem. Some of the less quantifiable issues associated with the social impacts of electricity generating activities have been covered by multicriteria methods, using well recognised methods like the ones from the outranking family or the Analytic Hierarchy Process (AHP), or by the economic valuation of externalities like the ExternE study. The literature extensively debates the methods available and provides some examples of application. Most of these examples focus on the analysis of specific technologies, on the comparison of different power production options or on the evaluation of power generation expansion scenarios for small systems. However, the integration of the cost, emissions and social impact of a full scale real National electricity planning that combines multiobjective optimisation models and models dealing with discrete alternative options, is still not fully explored.

Several barriers which prevent renewables from being competitive and fully integrated in the current power market have been identified. Although, renewable energies have in general much lower emissions than conventional thermal power, past studies have demonstrated that renewable energy technologies are not free from negative impacts, both on the energy system itself and in regard to public acceptance. In the particular case of wind, relevant negative impacts on the ecosystem, noise complaints and negative impacts on the landscape were reported. In addition to these social impacts, the integration of technologies of variable output like wind power in the grid poses an additional problem to the grid management that should be addressed during the planning process. Aspects such as the increase on reserve rudiments to deal with unexpected power output variations, the increase on the frequency of start ups and the possible reduction of the load level of thermal power plants are particularly relevant. Thus, the evaluation of the impact of large scale wind power on the system's economic and environmental performance cannot be based on simple assumptions of substitution of electricity generation technologies and heavily depends on the specific characteristics of the system under analysis.

In general, there appears to be a consensual view, that designing a sustainable energy plan, is a multidisciplinary process and implies addressing and integrating technical, environmental, economic and social dimensions. However, the integration of the relevant dimensions of sustainable energy planning poses an important challenge to researchers. This quest for integration is precisely the focus of this study, providing the decision makers with a comprehensive and feasible decision support system that will assist them in identifying optimal energy solutions. The electricity system expansion and operation strategies should derive from an integrated planning process of the overall electricity system, rather than by direct comparison of technologies. The study proposes a possible model in which all these dimensions are included and fully integrated, merging mathematical evidence based on optimisation procedures with value judgments.

Based on the literature review, a framework for electricity planning was proposed taking into consideration the multiple objectives involved, using optimisation procedures where possible, and incorporating value judgments in regard to social acceptability of proposed generation plans. The research demonstrated the applicability of the new Integrated Electricity Planning Model to the Portuguese power system planning. The system was analysed and modelled taking into consideration both specific technical characteristics and social impacts.

Two optimisation models, one linear and one non linear, were developed for Portugal, combining economic and environmental objectives with legal, demand and system constraints. The difference between the models laid mainly on the assumed impact of wind power on the thermal power system operation. From the models, investment and generation plans for the electricity system, which minimised costs and CO_2 emissions during the next 10 years, were obtained.

The models developed demonstrate the interaction between all the members of the electricity system. A particular generation option in the system must not be analysed in isolation and its impact on the overall electricity system must be included in the long term planning models. For the Portuguese case, increasing penetration of wind power in the system will have significant effects on the CCGT operation and the operating cost reduction and environmental gains are lower than those expected on the basis of simple substitution of technologies. In respect to the linear model these reductions in expectations arise from the low availability of the variable energy source, wind. The non linear model takes into consideration further impacts that large wind power will have on the power system operating conditions. The model computes the CCGT fuel cost and CO_2 emissions as functions of the installed wind power, using evidence of the reduction of the average load level of the CCGT plants and thus accounting for consequent loss of efficiency. The results show that CO_2 reduction is a more expensive process than what the linear model might lead the analyst to think. For example, to reach an average yearly CO_2 emission level equal to 20Mton, close to the objective proposed for the sector in the last Portuguese report under the Kyoto protocol[96], the cost would be 1.1% higher than the one obtained from the linear model and additional reductions become increasingly more costly. Under the base scenario conditions, the results of the non linear continuous model indicate that the least expensive way to achieve a CO_2 level equal to 20 Mton in Portugal is a strong investment in new CCGT and the continuous investment in new wind power plants during the period of the plan.

To integrate social concerns into the electricity planning decision process, a combination of Delphi and AHP methodologies for characterising and systematising experts' preferences was used. A group of experts was invited to participate in the process of evaluating electricity generation technologies against social criteria and a social index for each technology was developed. These social indexes were next applied to the optimal and close to optimal generation plans, resulting in an Average Social Index (ASI) for each of these plans, representing the overall expected social impact of each possible electricity generation strategy for the future. For this particular group of experts and for the analysed

[96] National allocation plan (2008-2012) (available in www.iambiente.pt).

case, the favoured solutions are the ones with reduced share of coal and high share of gas power plants.

The final result obtained from the Integrated Electricity Planning Model (IEPM) application is a set of plans describing the electricity generation scheduling for the next ten years, detailing monthly plans for the electricity production, yearly plans for the generation capacity expansion and specifying cost, CO_2 emissions, external energy dependency and an average social index.

Figure 8.1 presents an example of feasible electricity plans obtained for Portugal. The Figure represents the distribution of the total installed power in 2016 according to the REN forecast and the equivalent results obtained with the IEPM for 2017, for the minimal cost solution and for the Kyoto reference scenario (CO_2=20 Mton)[97] described by the financial cost optimal solution NLS4 and the non optimal solution NLS4.1. The ASI is presented along with the average cost and CO_2 emission values and with the external dependency. The non linear model as a part of the IEPM was used in the cases represented below.

According to the REN's (2005) forecasts for 2016, Special Regime Producers (SRP) are expected to represent about 35% of the total installed power in Portugal, followed by large hydro power with a 25% share and coal and natural gas power with a 20% share each. As the total SRP installed power is strongly constrained by the European Renewable Directive, the results of the IEPM solutions differ from the REN scenario mainly on the relative share of coal and natural gas sectors. The minimal financial cost solution requires a higher reliance on coal, with no investment in natural gas power plants. On the other hand, the imposition of maximum levels for CO_2 emissions leads to a move away from coal towards new investments in natural gas. However, it is worth recalling that the REN scenario derives from different models, based on different assumptions and backed up by large amounts of historical data and information that is not fully available to the researcher. The REN scenario is presented for information purposes only and a comparative evaluation is not appropriated. As illustrated in Figure 8.1, from the IEPM application the Decision Maker is equipped to make an informed decision based on the cost of electricity generation over the planning period, the total CO_2 emissions from the system, the ASI of each

[97] See Section V.5.1 for further detail.
The Kyoto reference scenario corresponds to an average CO_2 emission value equal to 0.379 ton/MWh for the 10 year planning period.

possible generation mix and the external dependency of any feasible electricity production plan.

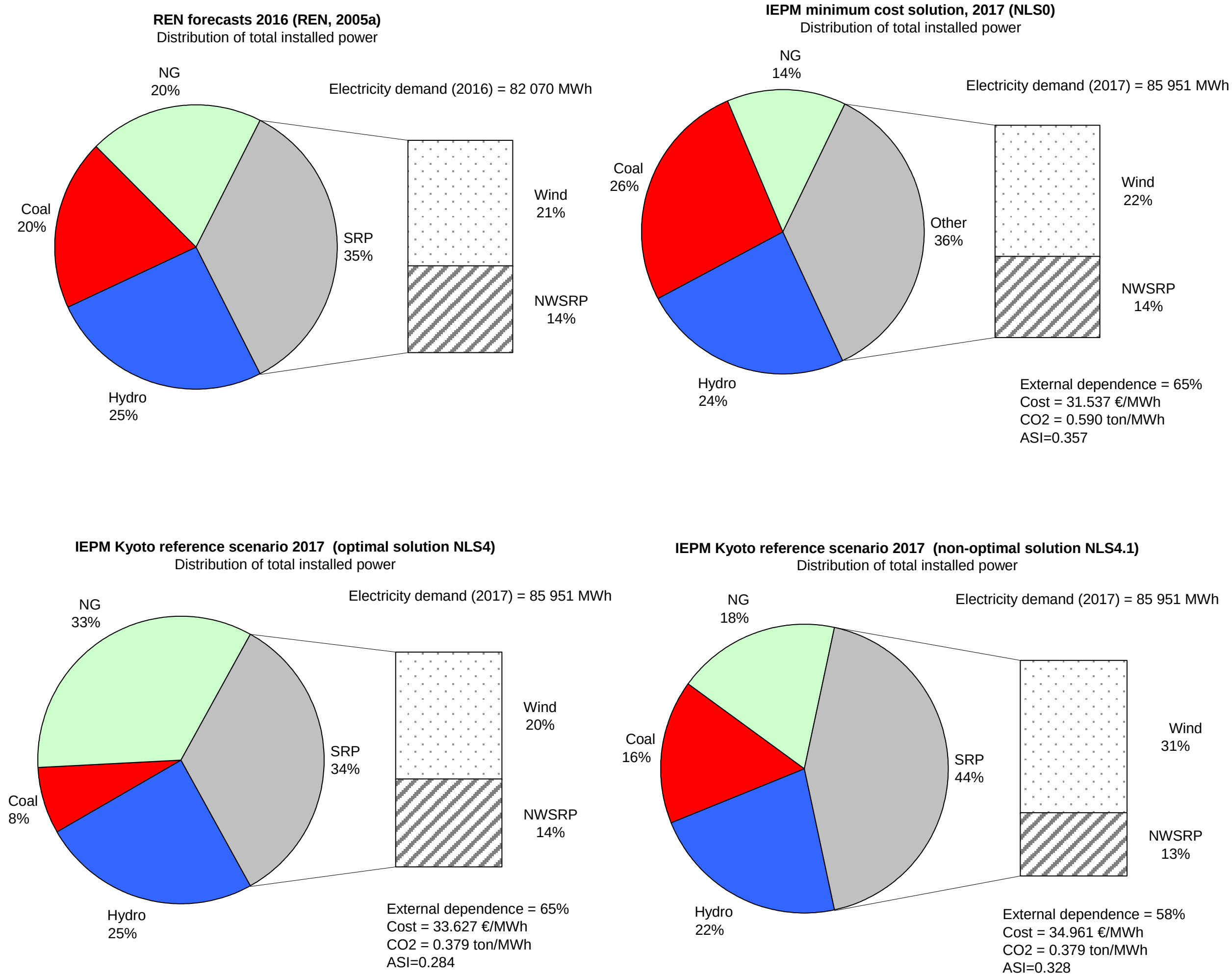

Figure 8.1- Electricity plans for the Portuguese power system.

Based on the literature review and on the illustrative application to the Portuguese case, it would appear that the IEPM is a valuable tool for energy decision makers and for the companies operating in the electricity market. It provides a structured methodology for the design of future energy strategies based on sustainable development principles, allowing for the adaptation of the proposed models to different energy systems or to changes in the political and regulatory environment.

For regions and countries with central electricity planning, the proposed methodology allows for the establishment of a number of electricity plans that are defensible from the cost, environmental and social point of view. Even in deregulated markets, broadly based central planning is still required for the definition of long term energy strategies. Further more, new plants must be developed in accordance with central plans to gain approval for construction and operation. Therefore, central planning may give medium and long term signals to the investors in the electricity generation market.

VIII.2 Contributions of the research

From the research conducted, important contributions to the long range electricity planning were made:

- An extensive collection of data in respect of Portugal, characterising future electricity generation technologies possibilities, power plants presently operating, regulation of the sector and future electricity demand.

- A description of the impacts of large scale wind power integration into the electricity systems and the quantification of some of these impacts for the Portuguese case.

- Multiple objective energy planning optimisation models integrating environmental and financial cost issues. The models were applied to the Portuguese case but these models can be adapted to different power systems and different planning periods.

- A set of financial cost optimal plans for the electricity sector in Portugal, detailing plans for new thermal and wind power plants installation over a ten year planning horizon. The plans identify the optimal timing and size of new generation capacity and the electricity production schedule during the planning period to meet the specified demand. Each of these plans may be regarded as either a minimal financial cost achievable at a specific CO_2 emissions level plan or the minimum CO_2 achievable for a certain financial cost plan.

- A detailed methodology for the integration of social concerns into the electricity planning process based on a participative methodology and involving a group of experts. The application of the proposed method to the Portuguese case, result in the computation of an Average Social Index for each optimal electricity expansion plan.

- The final outcome of the research is a structured, multidimensional participatory methodology for electricity planning (Integrated Electricity Planning Model) that may be used as a framework to support sustainable energy decisions. The proposed model, gives the final decision maker access to the financial cost, CO_2 emissions, social index and external dependency of any feasible electricity generation plan over the planning horizon.

VIII.3 Recommendations for the future

Regardless of the previously described outcomes, much remains to be done and this work should be seen as a precursor of future research projects. In the text of the thesis the major limitations of the models were pointed out, indicating also future possible approaches to deal with the recognised problems. Important areas requiring future research include[98]:

- The extension of the optimisation models:

    - including other objective functions as for example SO_2 or NO_x emissions or the total environmental damages;
    - integrating other renewable energy sources as variables instead of parameters;
    - integrating clean coal technologies and the possibility of CO_2 capture for thermal power plants, which would imply changing both the CO_2 emission and the cost functions;
    - including estimated grid costs for integration of decentralised electricity producers;
    - developing of a more sophisticated sub-model incorporating the impact of variable renewable generation technologies on other technologies. The model should integrate the short term operational planning and dispatching process with the long range planning models. The process should be

[98] This section only summarises the proposals for future research. A detailed description of these proposals may be found along the text, in particular in the conclusions of Chapter V and VI.

iterative and based on a complementary approach, coupling long term energy expansion plan with the results of short term operation strategies for each one of these plans. This issue is more extensively debated section V.8.1.

- The enrichment of the analysis of the social impact of the electricity expansion plans:

    - including other possible criteria and assessing also the relative importance of the quantitative aspects like cost or external dependency comparatively to the social aspects;
    - increasing the number of participants in the questionnaire phase, either focusing on experts or on representative stakeholders. A larger number of responses could be analysed a new insights could derive from using statistical tools like cluster analysis or factor analysis;
    - following other studies conducted already in other European countries (as described in section III.4.5 and IV.3.3.2), large scale surveys could be used to assess the general social attitude towards wind power in Portugal and the locals perception;

The implementation of the models embedded in the proposed methodology relied on the characterisation of the Portuguese system obtained from official reports and on the empirical data collected from a particular CCGT plant for the description of the characteristic curve of these plants. A benchmarking study, either at National or European level, of thermal power plants over their operating regime giving cost, performance and CO_2 emissions data to populate the models would be a particular benefit.

The involvement of central planners in the proposed decision making process would be of great benefit, not only by ensuring the accuracy of the data used in the mathematical elements of the process but, in addition would contribute significantly to the participation of experts in the AHP and Delphi analysis. Such involvement of the central planners would also assist in creating the appropriate climate for carrying out the above mentioned benchmarking study.

Finally, the aid to the decision making methodology developed may be adapted and used in other sectors with strong sustainable development commitments, as such requiring the assessment and integration of economic, environmental and social criteria. Some examples of these sectors may include transportation, waste management or the CO_2 storage.

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ANNEXES

ANNEX 1

Description of the present and future Portuguese electricity generating system (REN sustainability scenario).

Location	Plant type	2006[1] (MW)	2016[2] (MW)	Average load factor in 2006[1]
Sines	Coal	1192	1192	98.3%
Pêgo	Coal	628	628	85.9%
Tapada Outeiro	CCGT	990	990	46.9%
Ribatejo	CCGT	1176	1176	56.9%
Carregado	Gas	238		4.4%
Carregado	Fueloil	472		
Setubal	Fueloil	946		16.2%
Barreiro	Fueloil	56		34.9%
Tunes	Gasoil	198		0.1%
	Large hydro	4582	5805	
	Run of river	*2181*		*31.4%*[4]
	Storage	*2401*		*19.5%*[4]
	NWSRP	1626	3245	
	Small hydro	*286*	*570*	*40.0%*[4]
	Cogeneration	*1400*	*1875*	*39.5%*[4]
	Other[3]		*800*	
	Wind	1515	4750	*21.9%*[4]
Sines	Coal		4×450 = 1800	
Lavos	Coal		2×450 = 900	
Pego	CCGT		2×400 = 800	
Lavos	CCGT		400	
Carregado	CCGT		400	
Tunes	SCGT		250	
Tapada do Outeiro	SCGT		2×250 = 500	
Paraimo	SAD		50	
Valdigem	SAD		200	
Riba d'Ave	SAD		200	

(1) Source: DGGE(2007), EDP (2007), PEGOP(2006), Turbogas (2006), REN (2006b) REN and EDP websites.
(2) Source: REN (2005).
(3) Includes biomass, biogas, waves and tidal, wastes and photovoltaic.
(4) Based on electricity supplied to the grid.

ANNEX 2

Average fuel consumption, fuel cost and average CO_2 emissions.

Existing power plants

Plant type	Fuel consumption [1]	Efficiency (%) [2]	Fuel cost [3]	Fuel cost (€/MWh) [4]	CO_2 (ton/MWh) [5]
Coal	0.349 ton/MWh	40.2	56.7 €/ton	19.8	0.844
CCGT	174 m^3N/MWh	53.5	241 €/10^3m^3N	41.9	0.375
Fueloil	0.223 ton/MWh	40.0	202.6 €/ton	45.2	0.715
SCGT	266 m^3N /MWh	35.0	241 €/10^3m^3N	64.1	0.575

[1] Fuel consumption- average unit of fuel consumed (measured in tons of coal and fueloil and m^3N of natural gas) per MWh of electricity produced. Information obtained from power plants presently operating in the market (EDP, 2006a) and Turbogas (2005).

[2] Average efficiency (%) $= \dfrac{\text{Electricty produced in an year (MWh)}}{\text{Fuel consumed in an year (MWh)}} \times 100$, assuming the following calorific power for each fuel:

Coal - 25584 MJ/ton = 7.11 MWh/ton

Fueloil - 40193 MJ/ton = 11.16 MWh/ton

Natural gas - 42034 MJ/10^3m^3N = 11.68 MWh/10^3m^3N

[3] Fuel cost- average cost per unit of fuel consumed (measured in € per ton for coal and fueloil and € per m^3N of natural gas). Information obtained from power plants presently operating in the market (EDP, 2006b).

[4] Fuel cost (€/MWh) = [1]×[3]. Average cost per MWh of electricity produced.

[5] CO_2 – average CO_2 emissions (measured in tons) per MWh of electricity produced. Information obtained from power plants presently operating in the market (EDP, 2006a) and Turbogas (2005).

Candidate power plants

Plant type	Efficiency (%)	Fuel consumption	Fuel	Fuel cost (€/MWh)	CO_2 (ton/MWh)
SCPC[1]	46.0	0.305 ton/MWh	56.7 €/ton	17.3	0.738
CCGT[2]	57.0	163.4 m^3N/MWh	241.0 €/$10^3 m^3$N	39.4	0.353

[1] Super critical pulverised coal
[2] Combined cycle gas turbine
Efficiency- Information obtained from IEA/NEA (2005).

The average fuel consumption was calculated from the data for existing power plants. For simplicity reasons, average values for the efficiency of the power plants were used and it was assumed that the relationship $\frac{\text{Efficiency of the existing power plant (\%)}}{\text{Efficiency of the candidate power plant (\%)}}$ would be constant regardless of the operating regime.

$$\text{Fuel consumption of the candidate power plant} =$$

$$\frac{\text{Efficiency of the existing power plant (\%)}}{\text{Efficiency of the candidate power plant (\%)}} \times \text{Fuel consumption of the existing power plants}$$

$$\text{Fuel consumption of candidate coal plants} = \frac{40.2}{46} \times 0.349 = 0.305 \text{ ton/MWh}$$

$$\text{Fuel consumption of candidate gas plants} = \frac{53.55}{57} \times 174 = 163.4 \text{ m}^3\text{N/MWh}$$

CO_2 emissions calculated from data for existing power plants, assuming new higher efficiency values:

$$CO_2 \text{ emissions of candidate coal plants} = \frac{40.2}{46} \times 0.844 = 0.738 \text{ ton/MWh}$$

$$CO_2 \text{ emissions of candidate gas plants} = \frac{53.55}{57} \times 0.375 = 0.353 \text{ m}^3\text{N/MWh}$$

ANNEX 3

Average load factors

Month	Hydro			Wind	Small hydro (1)	Other SRP(3)	Fuel oil (4)
	Run of river (1)	Storage (1)	Storage (2)				
Jan.	48%	34%	14%	32%	54%	33%	23%
Feb.	51%	25%	10%	27%	49%	35%	22%
Mar.	52%	25%	6%	30%	57%	34%	14%
Apr.	48%	16%	3%	26%	49%	35%	6%
May	33%	13%	3%	20%	29%	32%	12%
Jun.	21%	11%	6%	17%	12%	30%	27%
Jul.	14%	14%	6%	19%	6%	34%	32%
Aug.	11%	11%	7%	17%	4%	33%	25%
Sep.	17%	11%	6%	16%	4%	35%	47%
Oct.	24%	13%	5%	29%	27%	34%	33%
Nov.	40%	42%	12%	37%	47%	35%	22%
Dec.	52%	55%	16%	46%	57%	38%	24%
Annual	*34%*	*23%*	*8%*	*27%*	*33%*	*34%*	*24%*

Source: REN, 2001- 2006 month data available online.

(1) Average regime.
(2) Dry regime (non electrical commitments).
(3) Cogeneration, biomass, biogas, waves and tidal, wastes and photovoltaic.
(4) Barreiro and Carregado (includes natural gas group).

ANNEX 4

Computation of the modelled electricity production.

Demand forecast

Month	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Jan.	5533	5759	5995	6241	6536	6844	7167	7506	7860	8231
Feb.	4868	5068	5276	5492	5751	6022	6307	6604	6916	7242
Mar.	5085	5293	5510	5736	6007	6291	6588	6898	7224	7565
Apr.	4268	4443	4625	4814	5042	5279	5529	5790	6063	6349
May	4518	4703	4896	5097	5337	5589	5853	6129	6419	6722
Jun.	4570	4758	4953	5156	5399	5654	5921	6200	6493	6799
Jul.	4962	5166	5377	5598	5862	6139	6428	6732	7049	7382
Aug.	4563	4750	4945	5148	5391	5645	5912	6191	6483	6789
Sep.	4663	4854	5053	5260	5509	5769	6041	6326	6625	6937
Oct.	4738	4933	5135	5345	5598	5862	6138	6428	6732	7049
Nov.	4693	4886	5086	5294	5544	5806	6080	6367	6667	6982
Dec.	5312	5530	5757	5993	6276	6572	6882	7207	7547	7903
Annual (GWh)	**57774**	**60142**	**62607**	**65174**	**68250**	**71471**	**74845**	**78377**	**82077**	**85951**
Peak load (MW)	**9900**	**10300**	**10716**	**11150**	**11681**	**12237**	**12819**	**13429**	**14070**	**14740**

Note: The demand forecast was based on REN (2005) yearly projections for electricity consumption and on the monthly pattern of the demand in 2006 obtained from REN website.

Installed power (MW)

Month	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Small hydro	410	427	444	460	482	505	529	555	570	570
Other SRP(1)	1789	1929	2079	2209	2302	2398	2499	2604	2675	2675
Run of river	2224	2224	2224	2224	2455	2455	2636	2636	2636	2636
Hydro storage	2358	2358	2358	2358	2496	2958	2958	3166	3166	2358
Fuel oil (2)	766	766	710	0	0	0	0	0	0	0

(1) Cogeneration, biomass, biogas, waves and tidal, wastes and photovoltaic.
(2) Barreiro and Carregado (includes natural gas group).

Non-modelled production includes:

- Production from run of river power plants, including small hydro plants (average regime).
- Production from hydro storage power plants (dry regime).
- Production from NWSRP.
- Production from fuel oil power plants (Barreiro and Carregado).

These values were computed using data presented in Annex 3.

Non modelled production (GWh)

Month	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Jan.	1765	1805	1839	1757	1885	1965	2064	2121	2144	2144
Feb.	1591	1629	1663	1594	1712	1774	1868	1915	1937	1937
Mar.	1680	1723	1762	1726	1855	1911	2016	2063	2088	2088
Apr.	1434	1475	1517	1527	1640	1681	1777	1816	1839	1839
May	1180	1217	1252	1225	1311	1350	1423	1459	1479	1479
Jun.	1015	1047	1071	962	1026	1068	1120	1154	1171	1171
Jul.	990	1027	1052	919	974	1021	1067	1104	1123	1123
Aug.	905	940	967	869	919	969	1009	1047	1065	1065
Sep.	1087	1122	1142	933	990	1035	1082	1118	1136	1136
Oct.	1221	1261	1289	1151	1226	1275	1338	1378	1400	1400
Nov.	1559	1600	1635	1560	1669	1742	1828	1881	1904	1904
Dec.	1961	2008	2048	1962	2104	2196	2305	2370	2397	2397
Annual	**16378**	**16844**	**17226**	**16176**	**17302**	**17969**	**18882**	**19409**	**19665**	**19665**
% fuel oil	10%	9%	9%	0%	0%	0%	0%	0%	0%	0%
% small hydro	7%	7%	7%	8%	8%	8%	8%	8%	8%	8%
% other SRP (1)	33%	34%	36%	41%	40%	40%	40%	40%	41%	41%
% hydro	50%	49%	48%	51%	52%	52%	52%	52%	51%	51%

(1) Cogeneration, biomass, biogas, waves and tidal, wastes and photovoltaic.

Modelled demand (GWh)

Month	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Jan.	3768	3954	4156	4484	4650	4879	5103	5385	5716	6087
Feb.	3277	3438	3613	3898	4039	4248	4439	4689	4979	5305
Mar.	3405	3571	3749	4011	4152	4380	4571	4835	5136	5477
Apr.	2833	2967	3107	3288	3402	3599	3752	3974	4224	4510
May	3338	3486	3644	3872	4026	4239	4430	4671	4940	5242
Jun.	3555	3711	3882	4193	4373	4586	4801	5046	5322	5628
Jul.	3972	4139	4325	4678	4888	5117	5362	5628	5927	6260
Aug.	3658	3810	3978	4279	4471	4677	4903	5144	5418	5724
Sep.	3576	3732	3912	4327	4518	4734	4959	5208	5488	5801
Oct.	3517	3672	3846	4194	4371	4587	4801	5050	5332	5650
Nov.	3135	3286	3451	3734	3875	4064	4252	4486	4763	5078
Dec.	3351	3522	3709	4031	4172	4375	4577	4836	5150	5506
Annual	**41385**	**43288**	**45371**	**48988**	**50938**	**53485**	**55948**	**58951**	**62395**	**66269**
% Demand	**72%**	**72%**	**72%**	**75%**	**75%**	**75%**	**75%**	**75%**	**76%**	**77%**

ANNEX 5

NWSRP excluding fuel and gas cogeneration (GWh)

Month	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Jan.	367	396	427	453	477	502	529	557	574	573
Feb.	333	360	389	414	436	459	483	509	525	525
Mar.	384	414	446	474	499	525	553	582	600	599
Apr.	356	385	416	442	466	490	516	544	560	560
May	290	315	342	366	385	406	428	451	465	465
Jun.	219	240	263	283	298	315	332	350	361	361
Jul.	230	253	279	301	318	335	354	373	385	385
Aug.	219	241	266	287	303	320	337	356	368	368
Sep.	223	246	271	292	309	326	344	363	375	375
Oct.	299	325	354	379	399	421	444	468	482	482
Nov.	351	380	411	437	460	485	511	538	554	554
Dec.	410	442	477	507	535	563	593	624	643	643
Annual	**3681**	**3997**	**4341**	**4633**	**4884**	**5148**	**5424**	**5713**	**5893**	**5891**

(1) Assuming that 1/3 of the cogeneration electricity production comes from biomass and 2/3 from fueloil or natural gas combustion.

ANNEX 6

Average hydro inflows (GWh)

Month	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Jan.	723	723	723	723	765	907	907	971	971	971
Feb.	379	379	379	379	401	476	476	509	509	509
Mar.	592	592	592	592	627	743	743	795	795	795
Apr.	340	340	340	340	360	426	426	456	456	456
May	191	191	191	191	202	240	240	257	257	257
Jun.	66	66	66	66	70	83	83	89	89	89
Jul.	48	48	48	48	51	60	60	64	64	64
Aug.	41	41	41	41	43	51	51	55	55	55
Sep.	46	46	46	46	49	58	58	62	62	62
Oct.	409	409	409	409	433	513	513	549	549	549
Nov.	498	498	498	498	527	625	625	668	668	668
Dec.	533	533	533	533	564	668	668	715	715	715
Annual	**3866**	**3866**	**3866**	**3866**	**4092**	**4850**	**4850**	**5191**	**5191**	**5191**

Note: The hydro inflows are based on REN, 2001- 2006 monthly data available online, assuming that these values would increase with the increasing of the hydro storage capacity.

ANNEX 7

GAMS code EPM

```
*************************************************************************
********************  COST OPTIMIZATION     ****************************
*************************************************************************

* 1a, 1b, 1c coal, 2a, 2b ccgt, 3a wind onshore, 3b wind offshore, 4 coal, 5 ccgt, 6 fueloil, 7 large hydro,
* 8 SCGT, 9 wind, 10 offshore"

Sets

    t years /2008*2017 /
    r(t) renyears /2010*2017/
    m months /1*12/
    i plants / 1a, 1b, 1c, 2a, 2b, 3a, 3b, 4, 5, 6, 8, 9 /
    k(i) new plants / 1a, 1b, 1c, 2a, 2b, 3a, 3b/
    l(i) existing plants / 4, 5, 6, 8, 9 /
    h hydro plants      /7/
    kt(k) new thermal power plants /1a, 1b, 1c, 2a, 2b/
    lt(l) non wind existing plants /4, 5, 6, 8/
    kw(k) new wind power plants / 3a, 3b/
    lw(l) existing wind power power plants /9/    ;

Parameters IC(k) investment cost of the new plants (€-MW)

   / 1a  1137000
     1b  1137000
     1c  1137000
     2a  517000
     2b  517000
     3a  1213000
     3b  1741000/;

Parameters FOM(k) fixed OM cost of the new plants (€-MW)

   / 1a   33800
     1b   33800
     1c   33800
     2a   11300
     2b   11300
     3a   26600
     3b   61300 /;

Parameters n(k) life time of the new plants

   / 1a   35
     1b   35
     1c   35
     2a   24
     2b   24
     3a   20
     3b   20 /;

Parameters CP(kt) modular capacity of the new plants  (MW)

    / 1a   300
      1b   450
```

1c 700
2a 330
2b 400 /;

Parameters VOM(i) variable OM cost of the plants (€-MWh)

/ 1a 2.6
1b 2.6
1c 2.6
2a 2.2
2b 2.2
3a 0
3b 0
4 2.85
5 2.48
6 2.48
8 2.25
9 0 /;

Parameters F(i) fuel cost of the plants (€-MWh)

/ 1a 17.3
1b 17.3
1c 17.3
2a 39.4
2b 39.4
3a 0
3b 0
4 19.9
5 42.0
6 45.2
8 64.1
9 0 /;

Parameters COEF(i) CO2 emission coefficient of the plants (t-MWh)

/ 1a 0.738
1b 0.738
1c 0.738
2a 0.353
2b 0.353
3a 0
3b 0
4 0.844
5 0.375
6 0.715
8 0.575
9 0 /;

Table Phi(m,i) availability factor of the plants

	1a	1b	1c	2a	2b	3a	3b	4	5	6	8	9
1	0.95	0.95	0.95	0.95	0.95	0.32	0.32	0.95	0.95	0.95	0.95	0.32
2	0.95	0.95	0.95	0.95	0.95	0.27	0.27	0.95	0.95	0.95	0.95	0.27
3	0.95	0.95	0.95	0.95	0.95	0.30	0.30	0.95	0.95	0.95	0.95	0.30
4	0.95	0.95	0.95	0.95	0.95	0.26	0.26	0.95	0.95	0.95	0.95	0.26
5	0.95	0.95	0.95	0.95	0.95	0.20	0.20	0.95	0.95	0.95	0.95	0.20
6	0.95	0.95	0.95	0.95	0.95	0.17	0.17	0.95	0.95	0.95	0.95	0.17
7	0.95	0.95	0.95	0.95	0.95	0.19	0.19	0.95	0.95	0.95	0.95	0.19
8	0.95	0.95	0.95	0.95	0.95	0.17	0.17	0.95	0.95	0.95	0.95	0.17

```
9    0.95    0.95      0.95    0.95     0.95    0.16    0.16    0.95    0.95    0.95    0.95    0.16
10   0.95    0.95      0.95    0.95     0.95    0.29    0.29    0.95    0.95    0.95    0.95    0.29
11   0.95    0.95      0.95    0.95     0.95    0.37    0.37    0.95    0.95    0.95    0.95    0.37
12   0.95    0.95      0.95    0.95     0.95    0.46    0.46    0.95    0.95    0.95    0.95    0.46 ;

Scalar COEFh cO2 emission coefficient for hydro plants /0/;

Table IP(t,l) installed power of the existing plants     (MW)

              4       5       6       8       9
2008       1820   2166   946.4   250     1515
2009       1820   2166   946.4   250     1515
2010       1820   2166   946.4   250     1515
2011       1820   2166   946.4   500     1515
2012       1820   2166   946.4   500     1515
2013       1820   2166     0     500     1515
2014       1820   2166     0     500     1515
2015       1820   2166     0     750     1515
2016       1820   2166     0     750     1515
2017       1820   2166     0     750     1515 ;

Parameter year(t) year to index

     /  2008   1
        2009   2
        2010   3
        2011   4
        2012   5
        2013   6
        2014   7
        2015   8
        2016   9
        2017  10    /;

Parameter IPh(t) installed power of the existing hydro plants    (MW)

     /  2008   4582
        2009   4582
        2010   4582
        2011   4582
        2012   4951
        2013   5413
        2014   5597
        2015   5805
        2016   5805
        2017   5805    /;

Parameter D(t) demand  (MWh)

     /  2008    57774098
        2009    60142258
        2010    62607489
        2011    65173770
        2012    68249972
        2013    71471371
        2014    74844820
        2015    78377495
        2016    82076913
        2017    85950943       /;
```

Table Dx(t,m) modelled demand

	1	2	3	4	5	6	7	8
2008	3767890	3277254	3404769	2833388	3337942	3555290	3971710	3658082
2009	3954122	3438287	3570920	2967182	3485927	3710607	4139000	3810250
2010	4156191	3612925	3748537	3107447	3643645	3882040	4324972	3977691
2011	4484027	3897544	4010539	3287713	3871911	4193162	4678270	4278577
2012	4650342	4039406	4152355	3401870	4026087	4373135	4887769	4471414
2013	4879336	4248105	4380102	3598904	4239354	4585595	5117203	4676671
2014	5103254	4439049	4571055	3751928	4429671	4800552	5361759	4902504
2015	5384865	4689009	4835052	3973665	4670523	5046180	5627686	5143811
2016	5715906	4979008	5136419	4223730	4939528	5322004	5926815	5418110
2017	6086890	5305446	5477395	4509897	5242488	5628462	6259550	5724102

	9	10	11	12
2008	3576375	3517093	3134642	3350798
2009	3731877	3672073	3285920	3522020
2010	3911520	3845811	3451006	3708975
2011	4327205	4193810	3734221	4030566
2012	4518222	4371188	3874735	4171965
2013	4733821	4587042	4063901	4375442
2014	4958504	4800801	4252172	4576958
2015	5207738	5049933	4485834	4836345
2016	5488047	5332070	4763263	5150104
2017	5800725	5649801	5077962	5506317 ;

Parameter PL(t) peak load

```
/2008   9900
 2009   10300
 2010   10716
 2011   11150
 2012   11681
 2013   12237
 2014   12819
 2015   13429
 2016   14070
 2017   14740   /;
```

Parameter IPNW(t) instaleld power NWSRP

```
 /  2008   2199
    2009   2355
    2010   2523
    2011   2669
    2012   2784
    2013   2904
    2014   3029
    2015   3159
    2016   3245
    2017   3245
 /
;
```

Parameter IPO(t) installed power non modelled

```
 /
  2008  766
  2009  766
```

2010	710
2011	0
2012	0
2013	0
2014	0
2015	0
2016	0
2017	0 /

;

Table PNWx(t,m) NWSRP excluding coal and gas cogeneration (MWh)

	1	2	3	4	5	6	7	8
2008	367361	333341	384216	356047	289670	218931	229924	218519
2009	395859	360110	413957	384638	314904	240056	253418	241146
2010	426642	389062	446079	415563	342281	263055	279043	265834
2011	452976	413788	473561	441972	365569	282531	300693	286683
2012	477051	435924	498721	465616	385435	298202	317568	302816
2013	502298	459138	525104	490411	406271	314639	335270	319740
2014	528771	483481	552769	516411	428121	331878	353837	337491
2015	556528	509004	581775	543673	451032	349956	373308	356107
2016	573607	524741	599621	560482	465226	361224	385486	367760
2017	573445	524583	599453	560313	465066	361078	385317	367595

	9	10	11	12
2008	222673	298999	351247	409895
2009	245777	325487	379721	442371
2010	270989	354242	410531	477480
2011	292277	378684	436830	507482
2012	308732	399331	460241	534562
2013	325994	420986	484793	562960
2014	344099	443695	510538	592738
2015	363086	467508	537532	623959
2016	374973	482275	554184	643195
2017	374805	482104	554015	643006;

Table SH(t,m) Small hydro production (average year) MWh

	1	2	3	4	5	6	7	8	9
2008	164212	135268	172730	144491	87724	35261	17246	11887	11394
2009	170945	140814	179812	150415	91321	36707	17953	12374	11862
2010	177954	146588	187184	156582	95065	38212	18689	12882	12348
2011	184238	151764	193795	162112	98422	39561	19349	13336	12784
2012	193082	159049	203097	169893	103147	41460	20277	13977	13398
2013	202349	166683	212845	178048	108098	43451	21251	14647	14041
2014	212062	174684	223062	186594	113286	45536	22271	15351	14715
2015	222241	183069	233769	195551	118724	47722	23340	16087	15421
2016	228295	188056	240137	200877	121958	49022	23976	16526	15841
2017	228295	188056	240137	200877	121958	49022	23976	16526	15841

	10	11	12
2008	83874	138472	172973
2009	87313	144149	180065
2010	90893	150059	187447
2011	94103	155359	194067
2012	98620	162816	203382
2013	103353	170631	213144
2014	108314	178821	223375
2015	113513	187405	234097

2016	116606	192510	240474
2017	116606	192510	240474 ;

Table PNMH(t,m) hydro power production non modelled (MWh)

	1	2	3	4	5	6	7	8
2008	1037596	920517	974720	806995	594309	438931	339659	311388
2009	1037596	920517	974720	806995	594309	438931	339659	311388
2010	1037596	920517	974720	806995	594309	438931	339659	311388
2011	1037596	920517	974720	806995	594309	438931	339659	311388
2012	1134538	1008660	1070951	888877	653628	480078	369905	338018
2013	1181336	1040931	1092601	897251	664044	499279	391653	362705
2014	1246342	1102442	1162936	959450	708085	527026	410263	377793
2015	1267411	1116971	1172683	963220	712775	535670	420054	388907
2016	1267411	1116971	1172683	963220	712775	535670	420054	388907
2017	1267411	1116971	1172683	963220	712775	535670	420054	388907

	9	10	11	12
2008	363546	490499	844018	1143739
2009	363546	490499	844018	1143739
2010	363546	490499	844018	1143739
2011	363546	490499	844018	1143739
2012	396818	537092	922389	1249659
2013	416214	555902	962554	1305302
2014	437745	588008	1014560	1375272
2015	446477	596476	1032644	1400324
2016	446477	596476	1032644	1400324
2017	446477	596476	1032644	1400324 ;

Table afl(t,m) modelled storage (MWh)

	1	2	3	4	5	6	7	8
2008	1921313	214461	481668	296927	138002	-32000	-63000	-85167
2009	484313	214461	481668	296927	138002	-32000	-63000	-85167
2010	484313	214461	481668	296927	138002	-32000	-63000	-85167
2011	484313	214461	481668	296927	138002	-32000	-63000	-85167
2012	512657	227012	509857	314304	146079	-33873	-66687	-90151
2013	607548	269031	604230	372480	173117	-40142	-79031	-106838
2014	607548	269031	604230	372480	173117	-40142	-79031	-106838
2015	650269	287949	646718	398672	185290	-42965	-84588	-114350
2016	650269	287949	646718	398672	185290	-42965	-84588	-114350
2017	650269	287949	646718	398672	185290	-42965	-84588	-114350

	9	10	11	12
2008	-53000	313167	292833	248667
2009	-53000	313167	292833	248667
2010	-53000	313167	292833	248667
2011	-53000	313167	292833	248667
2012	-561002	331494	309971	263220
2013	-66486	392853	367346	311941
2014	-66486	392853	367346	311941
2015	-71161	420477	393177	333876
2016	-71161	420477	393177	333876
2017	-71161	420477	393177	-1103124

*Notes:
*January 2008 includes 1437 GWh from initial reserve.

```
*December 2017 subtracts 1437 to ensure that final reserve = intial reserve
*negative values in months with low water inflows. Means that hydro production
* in that months is restricted to the non modelled or comes from
* the water accumulated from previous months
;

Parameter delta(m) hours of the  month


    / 1     744
      2     672
      3     744
      4     720
      5     744
      6     720
      7     744
      8     744
      9     720
      10     744
      11     720
      12     744    /;

Scalar j interest rate /0.05/ ;
Scalar EC esmission cost /22/ ;
Scalar LTG loss thermal group /392/ ;
Scalar LHG loss hydro group/315/ ;
Scalar Q3 non-available capacity wind/0.73/ ;
Scalar Q7 non-available capacity hydro/0.3/ ;
Scalar QNW non-available capacity NWSRP/0.5/ ;
Scalar RM reference margin/0.052/ ;

Variables

      IPN(t,k) installed power
      P(t,m,i)  power output
      theta(t,kt) modular thermal power
      ph(t,m) hydro power output
      tc total cost
      co cO2 emissions
      Res(t,m) reserve

;

Positive variable IPN;
Positive variable P;
positive variable Ph;
integer variable theta;
Positive variable res;

IPN.up(t,k)=10000;
P.up(t,m,i)=10000;
theta.up(t,kt)=25;
ph.up(t,m)=2000;

Equations

      totalCO define objective function
      totalcost define objective function
      demand(t,m) observe demand
      capacity(t,kt) modular capacity
```

```
        reference(t) observe RM
        powerk(t,m,kt) observe power limits for new plants
        powerl(t,m,lt) observe power limits for existing plants
        ren(r) observe renewable limits
        windk(t,m,kw) observe wind priority
        windl (t,m,lw) observe wind priority
        windon(t,kw) observe wind onshore potential
        windoff(t,kw) observe wind offshore potential
        reference2(t) avoid unecessary capacity when minimizing emissions
        COconstraint observe CO limits
        acumulated(t,k) observe increasing IPN
        reserve(t,m) reserve
        reserve1(t) reserve in Jan
        reserve2(t) reserve in Feb
        reserve3(t) reserve in Mar
        reserve4(t) reserve in Apr
        reserve5(t) reserve in May
        reserve6(t) reserve in Jun
        reserve7(t) reserve in Jul
        reserve8(t) reserve in Aug
        reserve9(t) reserve in Sept
        reserve10(t) reserve in Oct
        reserve11(t) reserve in Nov
        reserve12(t) reserve in Dec
        minRes(t,m) minimum reserve
        maxRes(t,m) maximum reserve
        GNminimum(t,m) flexibility to the system

;

totalCO.. co=e=sum((t,m,i),COEF(i)*P(t,m,i)*delta(m))+sum((t,m),COEFh*Ph(t,m)*delta(m));

totalcost.. tc=e=(sum((t,k),(j*power((1+j),n(k))/(power((1+j),n(k))-
1)*IC(k)+FOM(k))*IPN(t,k)*power((1+j),-year(t)))
        +sum((t,m,i),(VOM(i)+F(i)+COEF(i)*EC)*P(t,m,i)*delta(m)*power((1+j),-year(t))))/1000;

demand(t,m).. sum(i,P(t,m,i))+PH(t,m)=g=Dx(t,m)/delta(m);

powerk(t,m,kt).. P(t,m,kt)=l=IPN(t,kt)*phi(m,kt);

powerl(t,m,lt).. P(t,m,lt)=l=IP(t,lt)*phi(m,lt);

reserve1(t)..  res(t,'1')=e=res(t-1,'12')+afl(t,'1')-Ph(t,'1')*delta('1');
reserve2(t)..  res(t,'2')=e=res(t,'1')+afl(t,'2')-Ph(t,'2')*delta('2');
reserve3(t)..  res(t,'3')=e=res(t,'2')+afl(t,'3')-Ph(t,'3')*delta('3');
reserve4(t)..  res(t,'4')=e=res(t,'3')+afl(t,'4')-Ph(t,'4')*delta('4');
reserve5(t)..  res(t,'5')=e=res(t,'4')+afl(t,'5')-Ph(t,'5')*delta('5');
reserve6(t)..  res(t,'6')=e=res(t,'5')+afl(t,'6')-Ph(t,'6')*delta('6');
reserve7(t)..  res(t,'7')=e=res(t,'6')+afl(t,'7')-Ph(t,'7')*delta('7');
reserve8(t)..  res(t,'8')=e=res(t,'7')+afl(t,'8')-Ph(t,'8')*delta('8');
reserve9(t)..  res(t,'9')=e=res(t,'8')+afl(t,'9')-Ph(t,'9')*delta('9');
reserve10(t).. res(t,'10')=e=res(t,'9')+afl(t,'10')-Ph(t,'10')*delta('10');
reserve11(t).. res(t,'11')=e=res(t,'10')+afl(t,'11')-Ph(t,'11')*delta('11');
reserve12(t).. res(t,'12')=e=res(t,'11')+afl(t,'12')-Ph(t,'12')*delta('12');

minRes(t,m)..    res(t,m)=g=1200000;

maxRes(t,m).. res(t,m)=l=3000000;

capacity(t,kt).. IPN(t,kt)=e=theta(t,kt)*CP(kt);
```

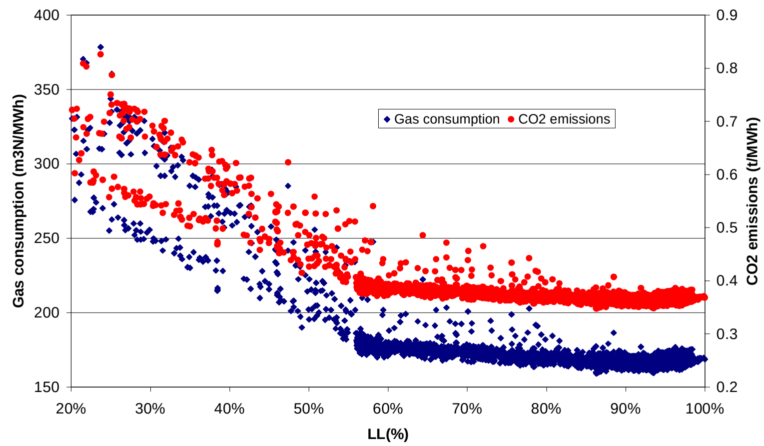
```
reference(t).. sum(l,IP(t,l))+sum(k,IPN(t,k))+IPh(t)+IPNW(t)+IPO(t)-
(Q3*(IPN(t,'3a')+IPN(t,'3b')+IP(t,'9'))+Q7*IPh(t)
        +QNW*IPNW(t)+LTG+LHG)-PL(t)-
RM*(sum(l,IP(t,l))+sum(k,IPN(t,k))+IPh(t)+IPNW(t)+IPO(t))=g=0;

reference2(t).. sum(l,IP(t,l))+sum(k,IPN(t,k))+IPh(t)+IPNW(t)+IPO(t)-(Q3*(IPN(t,'3a')+IPN(t,'3b')+IP(t,'9'))
        +Q7*IPh(t)+QNW*IPNW(t)+LTG+LHG)-PL(t)-
(RM+.2)*(sum(l,IP(t,l))+sum(k,IPN(t,k))+IPh(t)+IPNW(t)+IPO(t))=l=0;

ren(r).. sum(m,((P(r,m,'3a')+P(r,m,'3b')+P(r,m,'9')+Ph(r,m)*1.22)*delta(m)))+sum(m,Pnmh(r,m)*1.22)
        +sum(m,PNWx(r,m)-SH(r,m)+SH(r,m)*1.22)=g=0.39*D(r);

windk(t,m,kw).. P(t,m,kw)=e=IPN(t,kw)*phi(m,kw);

windl(t,m,lw).. P(t,m,lw)=e=IP(t,lw)*phi(m,lw);

windon(t,kw).. IPN(t,'3a')=l=6500;

windoff(t,kw).. IPN(t,'3b')=l=1000;

acumulated(t,k).. IPN(t,k)=g=IPN(t-1,k);

COconstraint.. sum((t,m,i),COEF(i)*P(t,m,i)*delta(m))+sum((t,m),COEFh*Ph(t,m)*delta(m))=l=2.0e8;

GNminimum(t,m)..      P(t,m,'2a')+P(t,m,'2b')+P(t,m,'5')=g=310;


Model windtotal / totalcost, demand, capacity, powerk, powerl, reference,
              windk, windl, windon, windoff, acumulated, totalco, reserve1,reserve2, reserve3,
              reserve4, reserve5, reserve6, reserve7, reserve8, reserve9, reserve10, reserve11,
              reserve12, minRes, maxRes, ren,  gnminimum/;


option optcr = 0.0 ;
OPTION RESLIM = 5000000;
windtotal.iterlim =10000000;

option minlp=baron;

Solve windtotal minimizing tc using minlp;

parameter IPcoal(t);
parameter IPgas(t);
parameter IPwind(t);
IPcoal(t)=IPN.l(t,'1a')+IPN.l(t,'1b')+IPN.l(t,'1c');
IPgas(t)=IPN.l(t,'2a')+IPN.l(t,'2b');
IPwind(t)=IPN.l(t,'3a')+IPN.l(t,'3b');

parameter PcoalNew total production of coal new;
parameter PcoalOld total production of coal old;
parameter PgasNew total production of gas new;
parameter PgasOld total production of gas old;
parameter Pwind total production of wind;

PcoalNew= sum((m),(P.l('2017',m,'1a')+P.l('2017',m,'1b')+P.l('2017',m,'1c'))*delta(m));
PgasNew= sum((m),(P.l('2017',m,'2a')+P.l('2017',m,'2b'))*delta(m));
PcoalOld= sum((m),P.l('2017',m,'4')*delta(m));
PgasOld= sum((m),P.l('2017',m,'5')*delta(m));
```

```
Pwind= sum((m),(P.l('2017',m,'3a')+P.l('2017',m,'3b')+P.l('2017',m,'9'))*delta(m));
parameter H2017 total hydro production;
H2017=sum((m),ph.l('2017',m)*delta(m));

parameter P2017 total production in 2017;
P2017=PcoalNew+PgasNew+Pcoalold+PgasOld+Pwind+H2017;

Parameter VarCost 2017 variable production cost;

VarCost= sum((m,i),(VOM(i)+F(i)+COEF(i)*EC)*P.l('2017',m,i)*delta(m))

;
parameter CostP(i) variable cost of plant i;

CostP(i)= VOM(i)+F(i)+COEF(i)*EC;

Parameter AvVar2017  variable production cost 2017;

AvVar2017=VarCost/sum((m),Dx('2017',m));

parameter AnnualCost(t) annual cost;

AnnualCost(t)= (sum((k),(j*power((1+j),n(k))/(power((1+j),n(k))-
1)*IC(k)+FOM(k))*IPN.l(t,k)*power((1+j),-year(t)))+
              sum((m,i),(VOM(i)+F(i)+COEF(i)*EC)*P.l(t,m,i)*power((1+j),-year(t))*delta(m)))/1000 ;

parameter AnnualCO(t) annual CO2;

AnnualCO(t)= sum((m,i),COEF(i)*P.l(t,m,i)*delta(m)+COEFh*Ph.l(t,m)*delta(m));

parameter AVcost average cost;

AVcost=(sum((t,k),(j*power((1+j),n(k))/(power((1+j),n(k))-1)*IC(k)+FOM(k))*IPN.l(t,k)*power((1+j),-
year(t)))
        +sum((t,m,i),(VOM(i)+F(i)+COEF(i)*EC)*P.l(t,m,i)*delta(m)*power((1+j),-
year(t))))/sum((t,m),Dx(t,m));

parameter AVCO average emissions;

AVCO=(sum((t,m,i),COEF(i)*P.l(t,m,i)*delta(m))+sum((t,m),COEFh*Ph.l(t,m)*delta(m)))/sum((t,m),Dx(t,
m));

display AVcost, AVCO;
display AnnualCost, AnnualCO;
display AvVar2017;

display PcoalNew, PgasNew, Pcoalold, PgasOld, Pwind, H2017, P2017;
display IPcoal, IPgas, IPwind;
```

ANNEX 8

Characteristic curve of the CCGT.

Information supplied by a CCGT company operating in the Iberian market:



The following equations present the quadratic regression analyses, relating the load level of the existing CCGT power plant with the specific fuel consumption and the CO_2 emission factor. The statistical significance of the results is also presented.

$$\text{SFC}\,(\text{m}^3\text{N/MWh}) = \underset{(128.1)\,*}{411.16\,\text{LL}^2} - \underset{(-145.8)\,*}{678.06\text{LL}} + \underset{(274.6)\,*}{442.11}$$

R^2=0.84

Fstatistic=19511

$$\text{COEF}\,(\text{ton/MWh}) = \underset{(128.1)\,*}{0.898\text{LL}^2} - \underset{(-145.8)\,*}{1.481\,\text{LL}} + \underset{(274.6)\,*}{0.964}$$

R^2=0.84

Fstatistic=19511

where SFC is the specific gas consumption of the CCGT plants in the system(m^3N/MWh), LL is the operating load level, and COEF is the specific CO_2 emissions of the CCGT plants in the system (ton/MWh). R^2 is the determination coefficient of the regression. The number in brackets are the t-statistics and * indicates statistical significance at 95% level.

For the new CCGT it was assumed that the shape of the relationship would be the same, but the expected higher efficiency leads to new functions. According to Tables 5.1 and 5.4, the average efficiency of new CCGT is expected to be 57% and the average efficiency of existing CCGT is 54%. For simplicity reasons, it was assumed that the 0.54/0.57 relationship would hold regardless of the output or load level of the power plants. The following equations describe the assumed relationships for the new CCGT:

$$\mathrm{SFC}\,(\mathrm{m^3N/MWh}) = 386.28\,\mathrm{LL}^2 - 637.02\mathrm{LL} + 415.35$$

$$\mathrm{COEF}\,(\mathrm{ton/MWh}) = 0.843\mathrm{LL}^2 - 1.391\,\mathrm{LL} + 0.907$$

ANNEX 9

CCGT load distribution

Annex 9.1 Quadratic CCGT characteristic curves

According to Section V.6.2, the NLEPM assumes a theoretical distribution of the load for the CCGT system during each interval of the planning period:

- each CCGT subsystems will be operating at average load levels (characterised by equations 5.31-5.34) for producing 50% of their electricity supply;
- each CCGT subsystems will be operating at a load level 10% higher than the average for producing 25% of their electricity supply;
- each CCGT subsystems will be operating at a load level 10% lower than the average for producing 25% of their electricity supply;

As an example, if the installed wind power is equal to 8000 MW in year t, from equation 5.30 the average load level of the CCGT system the model is equal to:

$$\overline{LL}_{CCGT} = -5.178 \times 10^{-5} \times 8000 + 0.914 = 0.50 \qquad :$$

Thus:

- each CCGT subsystems will be operating at average load levels equal to 50% for producing 50% of their electricity supply in each month of year t;
- each CCGT subsystems will be operating at a load level equal to 40% to produce 25% of their electricity supply in each month of year t;
- each each CCGT subsystems will be operating at a load level equal to 60% to produce the remaining 25% of their electricity supply in each month of year t.

And, from equations 5.37, 5.41 and 5.45 the SFC of the existing CCGT subsystem may be computed for the assumed distribution in year t:

25%	$\left(SFC_{5t}\right)_a = 1.10\times10^{-6}\left(8000\right)^2 + 4.66\times10^{-4}\times8000+162.6 = 236.9\ m^3/MWh$

50%	$\left(SFC_{5t}\right)_b = 1.10\times10^{-6}\left(8000\right)^2 - 3.79\times10^{-3}\times8000+165.8 = 206.0\ m^3\ /MWh$

25%	$\left(SFC_{5t}\right)_c = 1.10\times10^{-6}\left(8000\right)^2 - 8.05\times10^{-3}\times8000+177.3 = 187.3\ m^3/MWh$

Assuming that the electricity production from CCGT in a certain month of year t is equal to 1000 GWh, the total gas consumption would be:

$$\text{Gas consumption} = 236.9\times(0.25\times1000000)+206.0\times(0.50\times1000000)+187.3\times(0.25\times1000000)$$

Gas consumption = 210.1×10^6 m^3

If no load distribution was taken into account and only average functions were used to characterise each CCGT subsystem, the model would be implicitly assuming that all CCGT were operating at the same load level and the total gas consumption for this example would be:

$$\text{Gas consumption} = 206.0\times1000000$$

Gas consumption = 206.0×10^6 m^3

This simple example demonstrates the need to know the load distribution across the CCGT system or at least to assume a theoretical distribution of the load in order that the model reflects a more realistic situation.

Annex 9.2 Linear CCGT characteristic curves

Even if the characteristic curves of the CCGT subsystems were considered linear, the need to assume a theoretical distribution of the load would remain. Assuming that the SFC of the existing CCGT subsystem could be obtained from:

25%	$\left(SFC_{5t}\right)_a = 2.14\times10^{-3}\left(IP_{9t}+IP_{3a,t}+IP_{3b,t}\right)+171.8$

50%	$\left(SFC_{5t}\right)_b = 2.14\times10^{-3}\left(IP_{9t}+IP_{3a,t}+IP_{3b,t}\right)+167.7$

25%	$\left(SFC_{5t}\right)_c = 2.14 \times 10^{-3} \left(IP_{9t} + IP_{3a,t} + IP_{3b,t}\right) + 163.5$

For the previous example with total installed wind power equal to 8000 MW and total electricity production from CCGT in a certain month of year t is equal to 1000 GWh, the total fuel consumption would be:

25%	$\left(SFC_{5t}\right)_a = 2.14 \times 10^{-3} \times 8000 + 171.8 = 188.9$ m^3/MWh

50%	$\left(SFC_{5t}\right)_b = 2.14 \times 10^{-3} \times 8000 + 167.7 = 195.5$ m^3/MWh

25%	$\left(SFC_{5t}\right)_c = 2.14 \times 10^{-3} \times 8000 + 163.5 = 191.3$ m^3/MWh

$$\text{Gas consumption} = 188.9 \times (0.25 \times 1000000) + 195.5 \times (0.50 \times 1000000) + 191.3 \times (0.25 \times 1000000)$$

Gas consumption = 192.8×10^6 m^3

If no load distribution was taken into account and only average functions were used to characterise each CCGT subsystem, the total gas consumption for this example would be:

Gas consumption = 195.5×1000000

Gas consumption = 195.5×10^6 m^3

Demonstrating once more the need to know or assume a theoretical load distribution across the CCGT system

ANNEX 10

GAMS code NLEPM

```
*************************************************************************
********************   COST OPTIMIZATION      ***************************
*************************************************************************

* 1a, 1b, 1c coal, 2a, 2b ccgt, 3a wind onshore, 3b wind offshore, 4 coal, 5 ccgt, 6 fueloil, 7 large hydro,
* 8 SCGT, 9 wind, 10 offshore"
```

Sets

```
    t years /2008*2017 /
    r(t) renyears /2010*2017/
    m months /1*12/
    i plants / 1a, 1b, 1c, 2a, 2b, 3a, 3b, 4, 5, 6, 8, 9 /
    k(i) new plants / 1a, 1b, 1c, 2a, 2b, 3a, 3b/
    l(i) existing plants / 4, 5, 6, 8, 9 /
    h hydro plants      /7/
    kt(k) new thermal power plants /1a, 1b, 1c, 2a, 2b/
    lt(l) non wind existing plants /4, 5, 6, 8/
    kw(k) new wind power plants / 3a, 3b/
    lw(l) existing wind power power plants /9/    ;
```

Parameters IC(k) investment cost of the new plants (€-MW)

```
   / 1a  1137000
     1b  1137000
     1c  1137000
     2a  517000
     2b  517000
     3a  1213000
     3b  1741000/;
```

Parameters FOM(k) fixed OM cost of the new plants (€-MW)

```
   / 1a   33800
     1b   33800
     1c   33800
     2a   11300
     2b   11300
     3a   26600
     3b   61300 /;
```

Parameters n(k) life time of the new plants

```
   / 1a   35
     1b   35
     1c   35
     2a   24
     2b   24
     3a   20
     3b   20 /;
```

Parameters CP(kt) modular capacity of the new plants (MW)

```
    / 1a   300
      1b   450
```

```
  1c   700
  2a   330
  2b   400 /;
```

Parameters VOM(i) variable OM cost of the plants   (€-MWh)

```
/ 1a   2.6
  1b   2.6
  1c   2.6
  2a   2.2
  2b   2.2
  3a   0
  3b   0
  4  2.85
  5  2.48
  6  2.48
  8  2.25
  9    0   /;
```

Parameters F(i) fuel cost of the plants   (€-MWh)

```
/ 1a   17.3
  1b   17.3
  1c   17.3
  2a   0
  2b   0
  3a   0
  3b   0
  4    19.9
  5    0
  6    45.2
  8    64.1
  9     0   /;
```

Parameters COEF(i) CO2 emission coefficient of the plants   (t-MWh)

```
/ 1a   0.738
  1b   0.738
  1c   0.738
  2a   0
  2b   0
  3a   0
  3b   0
  4    0.844
  5    0
  6    0.715
  8    0.575
  9    0   /;
```

Table Phi(m,i) availability factor of the plants

	1a	1b	1c	2a	2b	3a	3b	4	5	6	8	9
1	0.95	0.95	0.95	0.95	0.95	0.32	0.32	0.95	0.95	0.95	0.95	0.32
2	0.95	0.95	0.95	0.95	0.95	0.27	0.27	0.95	0.95	0.95	0.95	0.27
3	0.95	0.95	0.95	0.95	0.95	0.30	0.30	0.95	0.95	0.95	0.95	0.30
4	0.95	0.95	0.95	0.95	0.95	0.26	0.26	0.95	0.95	0.95	0.95	0.26
5	0.95	0.95	0.95	0.95	0.95	0.20	0.20	0.95	0.95	0.95	0.95	0.20
6	0.95	0.95	0.95	0.95	0.95	0.17	0.17	0.95	0.95	0.95	0.95	0.17
7	0.95	0.95	0.95	0.95	0.95	0.19	0.19	0.95	0.95	0.95	0.95	0.19
8	0.95	0.95	0.95	0.95	0.95	0.17	0.17	0.95	0.95	0.95	0.95	0.17

9	0.95	0.95	0.95	0.95	0.95	0.16	0.16	0.95	0.95	0.95	0.95	0.16
10	0.95	0.95	0.95	0.95	0.95	0.29	0.29	0.95	0.95	0.95	0.95	0.29
11	0.95	0.95	0.95	0.95	0.95	0.37	0.37	0.95	0.95	0.95	0.95	0.37
12	0.95	0.95	0.95	0.95	0.95	0.46	0.46	0.95	0.95	0.95	0.95	0.46 ;

Scalar COEFh cO2 emission coefficient for hydro plants /0/;

Table IP(t,l) installed power of the existing plants (MW)

	4	5	6	8	9
2008	1820	2166	946.4	250	1515
2009	1820	2166	946.4	250	1515
2010	1820	2166	946.4	250	1515
2011	1820	2166	946.4	500	1515
2012	1820	2166	946.4	500	1515
2013	1820	2166	0	500	1515
2014	1820	2166	0	500	1515
2015	1820	2166	0	750	1515
2016	1820	2166	0	750	1515
2017	1820	2166	0	750	1515 ;

Parameter year(t) year to index

/ 2008 1
2009 2
2010 3
2011 4
2012 5
2013 6
2014 7
2015 8
2016 9
2017 10 /;

Parameter IPh(t) installed power of the existing hydro plants (MW)

/ 2008 4582
2009 4582
2010 4582
2011 4582
2012 4951
2013 5413
2014 5597
2015 5805
2016 5805
2017 5805 /;

Parameter D(t) demand (MWh)

/ 2008 57774098
2009 60142258
2010 62607489
2011 65173770
2012 68249972
2013 71471371
2014 74844820
2015 78377495
2016 82076913
2017 85950943 /;

Table Dx(t,m) modelled demand

	1	2	3	4	5	6	7	8
2008	3767890	3277254	3404769	2833388	3337942	3555290	3971710	3658082
2009	3954122	3438287	3570920	2967182	3485927	3710607	4139000	3810250
2010	4156191	3612925	3748537	3107447	3643645	3882040	4324972	3977691
2011	4484027	3897544	4010539	3287713	3871911	4193162	4678270	4278577
2012	4650342	4039406	4152355	3401870	4026087	4373135	4887769	4471414
2013	4879336	4248105	4380102	3598904	4239354	4585595	5117203	4676671
2014	5103254	4439049	4571055	3751928	4429671	4800552	5361759	4902504
2015	5384865	4689009	4835052	3973665	4670523	5046180	5627686	5143811
2016	5715906	4979008	5136419	4223730	4939528	5322004	5926815	5418110
2017	6086890	5305446	5477395	4509897	5242488	5628462	6259550	5724102

	9	10	11	12
2008	3576375	3517093	3134642	3350798
2009	3731877	3672073	3285920	3522020
2010	3911520	3845811	3451006	3708975
2011	4327205	4193810	3734221	4030566
2012	4518222	4371188	3874735	4171965
2013	4733821	4587042	4063901	4375442
2014	4958504	4800801	4252172	4576958
2015	5207738	5049933	4485834	4836345
2016	5488047	5332070	4763263	5150104
2017	5800725	5649801	5077962	5506317 ;

Parameter PL(t) peak load

```
/2008     9900
 2009     10300
 2010     10716
 2011     11150
 2012     11681
 2013     12237
 2014     12819
 2015     13429
 2016     14070
 2017     14740    /;
```

Parameter IPNW(t) instaleld power NWSRP

```
  / 2008     2199
    2009     2355
    2010     2523
    2011     2669
    2012     2784
    2013     2904
    2014     3029
    2015     3159
    2016     3245
    2017     3245
 /
;
```

Parameter IPO(t) installed power non modelled

```
 /    2008  766
      2009  766
      2010  710
```

2011	0
2012	0
2013	0
2014	0
2015	0
2016	0
2017	0 /

;

Table PNWx(t,m) NWSRP excluding coal and gas cogeneration (MWh)

	1	2	3	4	5	6	7	8
2008	367361	333341	384216	356047	289670	218931	229924	218519
2009	395859	360110	413957	384638	314904	240056	253418	241146
2010	426642	389062	446079	415563	342281	263055	279043	265834
2011	452976	413788	473561	441972	365569	282531	300693	286683
2012	477051	435924	498721	465616	385435	298202	317568	302816
2013	502298	459138	525104	490411	406271	314639	335270	319740
2014	528771	483481	552769	516411	428121	331878	353837	337491
2015	556528	509004	581775	543673	451032	349956	373308	356107
2016	573607	524741	599621	560482	465226	361224	385486	367760
2017	573445	524583	599453	560313	465066	361078	385317	367595

	9	10	11	12
2008	222673	298999	351247	409895
2009	245777	325487	379721	442371
2010	270989	354242	410531	477480
2011	292277	378684	436830	507482
2012	308732	399331	460241	534562
2013	325994	420986	484793	562960
2014	344099	443695	510538	592738
2015	363086	467508	537532	623959
2016	374973	482275	554184	643195
2017	374805	482104	554015	643006;

Table SH(t,m) Small hydro production (average year) MWh

	1	2	3	4	5	6	7	8	9
2008	164212	135268	172730	144491	87724	35261	17246	11887	11394
2009	170945	140814	179812	150415	91321	36707	17953	12374	11862
2010	177954	146588	187184	156582	95065	38212	18689	12882	12348
2011	184238	151764	193795	162112	98422	39561	19349	13336	12784
2012	193082	159049	203097	169893	103147	41460	20277	13977	13398
2013	202349	166683	212845	178048	108098	43451	21251	14647	14041
2014	212062	174684	223062	186594	113286	45536	22271	15351	14715
2015	222241	183069	233769	195551	118724	47722	23340	16087	15421
2016	228295	188056	240137	200877	121958	49022	23976	16526	15841
2017	228295	188056	240137	200877	121958	49022	23976	16526	15841

	10	11	12
2008	83874	138472	172973
2009	87313	144149	180065
2010	90893	150059	187447
2011	94103	155359	194067
2012	98620	162816	203382
2013	103353	170631	213144
2014	108314	178821	223375
2015	113513	187405	234097
2016	116606	192510	240474

2017	116606	192510	240474 ;

Table PNMH(t,m) hydro power production non modelled (MWh)

	1	2	3	4	5	6	7	8
2008	1037596	920517	974720	806995	594309	438931	339659	311388
2009	1037596	920517	974720	806995	594309	438931	339659	311388
2010	1037596	920517	974720	806995	594309	438931	339659	311388
2011	1037596	920517	974720	806995	594309	438931	339659	311388
2012	1134538	1008660	1070951	888877	653628	480078	369905	338018
2013	1181336	1040931	1092601	897251	664044	499279	391653	362705
2014	1246342	1102442	1162936	959450	708085	527026	410263	377793
2015	1267411	1116971	1172683	963220	712775	535670	420054	388907
2016	1267411	1116971	1172683	963220	712775	535670	420054	388907
2017	1267411	1116971	1172683	963220	712775	535670	420054	388907

	9	10	11	12
2008	363546	490499	844018	1143739
2009	363546	490499	844018	1143739
2010	363546	490499	844018	1143739
2011	363546	490499	844018	1143739
2012	396818	537092	922389	1249659
2013	416214	555902	962554	1305302
2014	437745	588008	1014560	1375272
2015	446477	596476	1032644	1400324
2016	446477	596476	1032644	1400324
2017	446477	596476	1032644	1400324 ;

Table afl(t,m) modelled storage (MWh)

	1	2	3	4	5	6	7	8
2008	1921313	214461	481668	296927	138002	-32000	-63000	-85167
2009	484313	214461	481668	296927	138002	-32000	-63000	-85167
2010	484313	214461	481668	296927	138002	-32000	-63000	-85167
2011	484313	214461	481668	296927	138002	-32000	-63000	-85167
2012	512657	227012	509857	314304	146079	-33873	-66687	-90151
2013	607548	269031	604230	372480	173117	-40142	-79031	-106838
2014	607548	269031	604230	372480	173117	-40142	-79031	-106838
2015	650269	287949	646718	398672	185290	-42965	-84588	-114350
2016	650269	287949	646718	398672	185290	-42965	-84588	-114350
2017	650269	287949	646718	398672	185290	-42965	-84588	-114350

	9	10	11	12
2008	-53000	313167	292833	248667
2009	-53000	313167	292833	248667
2010	-53000	313167	292833	248667
2011	-53000	313167	292833	248667
2012	-561002	331494	309971	263220
2013	-66486	392853	367346	311941
2014	-66486	392853	367346	311941
2015	-71161	420477	393177	333876
2016	-71161	420477	393177	333876
2017	-71161	420477	393177	-1103124

*Notes:
*January 2008 includes 1437 GWh from initial reserve.
*December 2017 subtracts 1437 to ensure that final reserve = intial reserve
*negative values in months with low water inflows. Means that hydro production

```
* in that months is restricted to the non modelled or comes from
* the water accumulatedfrom previous months
;
Parameter delta(m) hours of the  month


     / 1     744
       2     672
       3     744
       4     720
       5     744
       6     720
       7     744
       8     744
       9     720
       10     744
       11     720
       12     744     /;

Scalar j interest rate /0.05/ ;
Scalar EC esmission cost /22/ ;
Scalar LTG loss thermal group /392/ ;
Scalar LHG loss hydro group/315/ ;
Scalar Q3 non-available capacity wind/0.73/ ;
Scalar Q7 non-available capacity hydro/0.3/ ;
Scalar QNW non-available capacity NWSRP/0.5/ ;
Scalar RM reference margin/0.052/ ;

Variables

        IPN(t,k) installed power
        P(t,m,i)  power output
        theta(t,kt) modular thermal power
        ph(t,m) hydro power output
        tc total cost
        co cO2 emissions
        Res(t,m) reserve
        GN(t) gas consumption new CCGT  plants
        GO(t) gas consumption old CCGT plants
        G1(t) auxiliar variable for gas consumption
        G2(t) auxiliar variable for gas consumption
        G3(t) auxiliar variable for gas consumption
        G4(t) auxiliar variable for gas consumption

        CON(t) COEF  new power plants
        COO(t) COEF  old power plants
         ;

Positive variable IPN;
Positive variable P;
positive variable Ph;
integer variable theta;
Positive variable res;
Positive variable gn;
Positive variable go;
Positive variable COn;
Positive variable COo;
IPN.up(t,k)=10000;
P.up(t,m,i)=10000;
theta.up(t,kt)=25;
```

```
ph.up(t,m)=2000;

GN.up(t)=500;
GO.up(t)=500;
CON.up(t)=1;
COO.up(t)=1;
```

Equations

```
        totalCO define objective function
        totalcost define objective function
        demand(t,m) observe demand
        capacity(t,kt) modular capacity
        reference(t) observe RM
        powerk(t,m,kt) observe power limits for new plants
        powerl(t,m,lt) observe power limits for existing plants
        ren(r) observe renewable limits
        windk(t,m,kw) observe wind priority
        windl (t,m,lw) observe wind priority
        windon(t,kw) observe wind onshore potential
        windoff(t,kw) observe wind offshore potential
        reference2(t) avoid unecessary capacity when minimizing emissions
        COconstraint observe CO limits
        acumulated(t,k) observe increasing IPN
        reserve(t,m) reserve
        reserve1(t) reserve in Jan
        reserve2(t) reserve in Feb
        reserve3(t) reserve in Mar
        reserve4(t) reserve in Apr
        reserve5(t) reserve in May
        reserve6(t) reserve in Jun
        reserve7(t) reserve in Jul
        reserve8(t) reserve in Aug
        reserve9(t) reserve in Sep
        reserve10(t) reserve in Oct
        reserve11(t) reserve in Nov
        reserve12(t) reserve in Dec
        minRes(t,m) minimum reserve
        maxRes(t,m) maximum reserve

        Gasnew1(t)      gas consumption new CCGT
        Gasold1(t)      gas consumption old CCGT
        COnew1(t)       CO2 new CCGT
        COold1(t)       CO2 old CCGT

        GNminimum(t,m) flexibility to the system

;

totalCO.. co=e=(sum((t,m,i),COEF(i)*P(t,m,i)*delta(m))+sum((t,m),COEFh*Ph(t,m)*delta(m))
          + sum((t,m),CON(t)*(P(t,m,'2a')+P(t,m,'2b'))*delta(m))
          + sum((t,m),COO(t)*P(t,m,'5')*delta(m)))/1000;


totalcost.. tc=e=(sum((t,k),(j*power((1+j),n(k))/(power((1+j),n(k))-
1)*IC(k)+FOM(k))*IPN(t,k)*power((1+j),-year(t)))
           +sum((t,m,i),(VOM(i)+F(i)+COEF(i)*EC)*P(t,m,i)*delta(m)*power((1+j),-year(t)))
           + sum((t,m),gn(t)*(P(t,m,'2a')+P(t,m,'2b'))*delta(m)*power((1+j),-year(t)))*241e-3
           +sum((t,m),go(t)*P(t,m,'5')*delta(m)*power((1+j),-year(t)))*241e-3
```

```
              + sum((t,m),CON(t)*(P(t,m,'2a')+P(t,m,'2b'))*delta(m)*power((1+j),-year(t)))*EC
              +sum((t,m),COO(t)*P(t,m,'5')*delta(m)*power((1+j),-year(t)))*EC)/1000000              ;

gasold1(t).. go(t)=e=(1.102e-6*(IPN(t,'3a')+IPN(t,'3b')+IP(t,'9'))*(IPN(t,'3a')+IPN(t,'3b')+IP(t,'9'))-
              3.792e-3*(IPN(t,'3a')+IPN(t,'3b')+IP(t,'9'))+165.8)*.5
              +(1.102e-6*(IPN(t,'3a')+IPN(t,'3b')+IP(t,'9'))*(IPN(t,'3a')+IPN(t,'3b')+IP(t,'9'))-
              8.050e-3*(IPN(t,'3a')+IPN(t,'3b')+IP(t,'9'))+177.26)*.25
              +(1.102e-6*(IPN(t,'3a')+IPN(t,'3b')+IP(t,'9'))*(IPN(t,'3a')+IPN(t,'3b')+IP(t,'9'))-
              4.6598e-4*(IPN(t,'3a')+IPN(t,'3b')+IP(t,'9'))+162.61)*.25
;

gasnew1(t).. gn(t)=e=go(t)*0.5355/.57;


COold1(t).. COo(t)=e=(2.407e-9*(IPN(t,'3a')+IPN(t,'3b')+IP(t,'9'))*(IPN(t,'3a')+IPN(t,'3b')+IP(t,'9'))
              -8.28e-6*(IPN(t,'3a')+IPN(t,'3b')+IP(t,'9'))+0.362)*.5 +
              (2.407e-9*(IPN(t,'3a')+IPN(t,'3b')+IP(t,'9'))*(IPN(t,'3a')+IPN(t,'3b')+IP(t,'9'))
              -1.758e-5*(IPN(t,'3a')+IPN(t,'3b')+IP(t,'9'))+0.387)*.25+
              (2.407e-9*(IPN(t,'3a')+IPN(t,'3b')+IP(t,'9'))*(IPN(t,'3a')+IPN(t,'3b')+IP(t,'9'))
              +1.017e-6*(IPN(t,'3a')+IPN(t,'3b')+IP(t,'9'))+0.355)*.25
;

COnew1(t).. COn(t)=e=coo(t)*0.5355/.57;


demand(t,m).. sum(i,P(t,m,i))+PH(t,m)=g=Dx(t,m)/delta(m);

powerk(t,m,kt).. P(t,m,kt)=l=IPN(t,kt)*phi(m,kt);

powerl(t,m,lt).. P(t,m,lt)=l=IP(t,lt)*phi(m,lt);

reserve1(t)..  res(t,'1')=e=res(t-1,'12')+afl(t,'1')-Ph(t,'1')*delta('1');
reserve2(t)..  res(t,'2')=e=res(t,'1')+afl(t,'2')-Ph(t,'2')*delta('2');
reserve3(t)..  res(t,'3')=e=res(t,'2')+afl(t,'3')-Ph(t,'3')*delta('3');
reserve4(t)..  res(t,'4')=e=res(t,'3')+afl(t,'4')-Ph(t,'4')*delta('4');
reserve5(t)..  res(t,'5')=e=res(t,'4')+afl(t,'5')-Ph(t,'5')*delta('5');
reserve6(t)..  res(t,'6')=e=res(t,'5')+afl(t,'6')-Ph(t,'6')*delta('6');
reserve7(t)..  res(t,'7')=e=res(t,'6')+afl(t,'7')-Ph(t,'7')*delta('7');
reserve8(t)..  res(t,'8')=e=res(t,'7')+afl(t,'8')-Ph(t,'8')*delta('8');
reserve9(t)..  res(t,'9')=e=res(t,'8')+afl(t,'9')-Ph(t,'9')*delta('9');
reserve10(t).. res(t,'10')=e=res(t,'9')+afl(t,'10')-Ph(t,'10')*delta('10');
reserve11(t).. res(t,'11')=e=res(t,'10')+afl(t,'11')-Ph(t,'11')*delta('11');
reserve12(t).. res(t,'12')=e=res(t,'11')+afl(t,'12')-Ph(t,'12')*delta('12');

minRes(t,m)..    res(t,m)=g=1200000;

maxRes(t,m).. res(t,m)=l=3000000;

capacity(t,kt).. IPN(t,kt)=e=theta(t,kt)*CP(kt);

reference(t).. sum(l,IP(t,l))+sum(k,IPN(t,k))+IPh(t)+IPNW(t)+IPO(t)-
(Q3*(IPN(t,'3a')+IPN(t,'3b')+IP(t,'9'))+Q7*IPh(t)
        +QNW*IPNW(t)+LTG+LHG)-PL(t)-
RM*(sum(l,IP(t,l))+sum(k,IPN(t,k))+IPh(t)+IPNW(t)+IPO(t))=g=0;

reference2(t).. sum(l,IP(t,l))+sum(k,IPN(t,k))+IPh(t)+IPNW(t)+IPO(t)-(Q3*(IPN(t,'3a')+IPN(t,'3b')+IP(t,'9'))
        +Q7*IPh(t)+QNW*IPNW(t)+LTG+LHG)-PL(t)-
(RM+.2)*(sum(l,IP(t,l))+sum(k,IPN(t,k))+IPh(t)+IPNW(t)+IPO(t))=l=0;

ren(r).. sum(m,((P(r,m,'3a')+P(r,m,'3b')+P(r,m,'9')+Ph(r,m)*1.22)*delta(m)))+sum(m,Pnmh(r,m)*1.22)
```

```
        +sum(m,PNWx(r,m)-SH(r,m)+SH(r,m)*1.22)=g=0.39*D(r);

windk(t,m,kw).. P(t,m,kw)=e=IPN(t,kw)*phi(m,kw);

windl(t,m,lw).. P(t,m,lw)=e=IP(t,lw)*phi(m,lw);

windon(t,kw).. IPN(t,'3a')=l=6500;

windoff(t,kw).. IPN(t,'3b')=l=1000;

acumulated(t,k).. IPN(t,k)=g=IPN(t-1,k);

COconstraint.. sum((t,m,i),COEF(i)*P(t,m,i)*delta(m))+sum((t,m),COEFh*Ph(t,m)*delta(m))
            + sum((t,m),CON(t)*(P(t,m,'2a')+P(t,m,'2b'))*delta(m))
            + sum((t,m),COO(t)*P(t,m,'5')*delta(m))=l=1.75e8;

GNminimum(t,m)..      P(t,m,'2a')+P(t,m,'2b')+P(t,m,'5')=g=310;


Model windtotal / totalco, totalcost, demand, capacity, powerk, powerl, reference,
              windk, windl, windon, windoff, acumulated, reserve1,reserve2, reserve3,
              reserve4, reserve5, reserve6, reserve7, reserve8, reserve9, reserve10, reserve11,
              reserve12, minRes, maxRes, gasold1, gasnew1,
              COold1, COnew1, ren, gnminimum/;


option optcr = 0.025;
OPTION RESLIM = 5000000;
windtotal.iterlim =10000000;


option minlp=BARON;


Solve windtotal minimizing tc using minlp;

display  gn.l, go.l, COn.l, COo.l;

parameter IPcoal(t);
parameter IPgas(t);
parameter IPwind(t);
IPcoal(t)=IPN.l(t,'1a')+IPN.l(t,'1b')+IPN.l(t,'1c');
IPgas(t)=IPN.l(t,'2a')+IPN.l(t,'2b');
IPwind(t)=IPN.l(t,'3a')+IPN.l(t,'3b');

parameter PcoalNew total production of coal new;
parameter PcoalOld total production of coal old;
parameter PgasNew total production of gas new;
parameter PgasOld total production of gas old;
parameter Pwind total production of wind;

PcoalNew= sum((m),(P.l('2017',m,'1a')+P.l('2017',m,'1b')+P.l('2017',m,'1c'))*delta(m));
PgasNew= sum((m),(P.l('2017',m,'2a')+P.l('2017',m,'2b'))*delta(m));
PcoalOld= sum((m),P.l('2017',m,'4')*delta(m));
PgasOld= sum((m),P.l('2017',m,'5')*delta(m));
Pwind= sum((m),(P.l('2017',m,'3a')+P.l('2017',m,'3b')+P.l('2017',m,'9'))*delta(m));

parameter H2017 total hydro production;
H2017=sum((m),ph.l('2017',m)*delta(m));
```

```
parameter P2017 total production in 2017;
P2017=PcoalNew+PgasNew+Pcoalold+PgasOld+Pwind+H2017;

Parameter VarCost 2017 variable production cost;

VarCost= sum((m,i),(VOM(i)+F(i)+COEF(i)*EC)*P.l('2017',m,i)*delta(m))
        +sum((m),gn.l('2017')*(P.l('2017',m,'2a')+P.l('2017',m,'2b'))*241e-3*delta(m))
        +sum((m),go.l('2017')*(P.l('2017',m,'5'))*241e-3*delta(m))
        +sum((m),COn.l('2017')*(P.l('2017',m,'2a')+P.l('2017',m,'2b'))*EC*delta(m))
        +sum((m),COo.l('2017')*(P.l('2017',m,'5'))*EC*delta(m)) ;
Parameter AvVar2017  variable production cost 2017;

AvVar2017=VarCost/sum((m),Dx('2017',m));

parameter AnnualCost(t) annual cost;

AnnualCost(t)= (sum((k),(j*power((1+j),n(k))/(power((1+j),n(k))-
1)*IC(k)+FOM(k))*IPN.l(t,k)*power((1+j),-year(t)))
               +sum((m,i),(VOM(i)+F(i)+COEF(i)*EC)*P.l(t,m,i)*power((1+j),-year(t))*delta(m)))/1000
               +(sum((m),gn.l(t)*(P.l(t,m,'2a')+P.l(t,m,'2b'))*delta(m)*power((1+j),-year(t)))*241e-3
               +sum((m),go.l(t)*P.l(t,m,'5')*delta(m)*power((1+j),-year(t)))*241e-3
               +sum((m),CON.l(t)*(P.l(t,m,'2a')+P.l(t,m,'2b'))*delta(m)*power((1+j),-year(t)))*EC
               +sum((m),COO.l(t)*P.l(t,m,'5')*delta(m)*power((1+j),-year(t)))*EC)/1000;


parameter AnnualCO(t) annual CO2;

AnnualCO(t)= sum((m,i),COEF(i)*P.l(t,m,i)*delta(m)+COEFh*Ph.l(t,m)*delta(m))
        + sum((m),CON.l(t)*(P.l(t,m,'2a')+P.l(t,m,'2b'))*delta(m))
        + sum((m),COO.l(t)*P.l(t,m,'5')*delta(m));     ;


parameter AVcost average cost;


AVcost=(sum((t,k),(j*power((1+j),n(k))/(power((1+j),n(k))-1)*IC(k)+FOM(k))*IPN.l(t,k)*power((1+j),-
year(t)))
               +sum((t,m,i),(VOM(i)+F(i)+COEF(i)*EC)*P.l(t,m,i)*delta(m)*power((1+j),-year(t)))
               + sum((t,m),gn.l(t)*(P.l(t,m,'2a')+P.l(t,m,'2b'))*delta(m)*power((1+j),-year(t)))*241e-3
               +sum((t,m),go.l(t)*P.l(t,m,'5')*delta(m)*power((1+j),-year(t)))*241e-3
               + sum((t,m),CON.l(t)*(P.l(t,m,'2a')+P.l(t,m,'2b'))*delta(m)*power((1+j),-year(t)))*EC
               +sum((t,m),COO.l(t)*P.l(t,m,'5')*delta(m)*power((1+j),-year(t)))*EC)/sum((t,m),Dx(t,m));

parameter AVCO average emissions;

AVCO=(sum((t,m,i),COEF(i)*P.l(t,m,i)*delta(m))+sum((t,m),COEFh*Ph.l(t,m)*delta(m))
    + sum ((t,m),CON.l(t)*(P.l(t,m,'2a')+P.l(t,m,'2b'))*delta(m))
    + sum ((t,m),COO.l(t)*P.l(t,m,'5')*delta(m)))/sum((t,m),Dx(t,m));

display AVcost, AVCO;
display AnnualCost, AnnualCO;
display AvVar2017;

display PcoalNew, PgasNew, Pcoalold, PgasOld, Pwind, H2017, P2017;
display IPcoal, IPgas, IPwind;
```

ANNEX 11

First solution of the NLEPM using BARON solver

Cost optimization	Run time (min)	Error	Absolute values	
			Cost (M€)	CO_2 (Mt)
NLS0	2.4	2.50%	16756	306
NLS1	5.9	2.50%	17315	258
NLS2	6.3	2.50%	17520	239
NLS3	5.6	2.50%	17850	225
NLS4	4.2	2.50%	18276	200
NLS5	14.2	2.50%	18773	175
NLS6	4.6	2.50%	18892	150
NLS7	4.6	2.50%	21474	138
NLS8[(1)]	27.6	46.40%	23598	135

[(1)] This is the only exception to the stopping criteria. The evolution of the output indicated that during these 28 minutes there were no signs of improvement of the results.

ANNEX 12

Delphi questionnaire (1st round)

EVALUATION OF THE IMPACTS OF DIFFERENT ALTERNATIVES FOR ELECTRICITY GENERATION

This is a multiple choice questionnaire, where the possible answers will appear when clicking in the grey fields.

Assume the necessity of increasing the available power in about 1000 MW. This may be accomplished by new coal, gas or wind power plants. The possible solutions may be described as follows:

Coal solution	
Description	2 new coal power plants, one with installed capacity equal to 700 MW and another one with installed capacity equal to 450 MW.
Placement	Close to large electricity consumption centres.
Characteristics	In each power station there will be one chimney 225 m high and one cooling tower. Each power plant may occupy an area of about 1.5 ha (0.015 km^2) and burns imported coal.
Examples	Presently two power stations operate in Portugal: one in Sines and another one in Pego. Please find attached a photo of a coal power plant presently operating in Portugal.

Gas solution	
Description	2 new combined cycle natural gas power plants, one with installed capacity equal to 660 MW and another one with installed capacity equal to 400 MW.
Placement	Close to large electricity consumption centres.
Characteristics	The 660 MW power station will have two chimneys. The 400 MW power station will have 1 chimney. All the chimneys will be 80 m high. Each power station will have a cooling tower. Each power station may occupy an area of about 1.5 ha (0.015 km^2). It burns imported natural gas.
Examples	Presently two CCGT operate in Portugal: one in Ribatejo (Carregado) and another one in Tapada do Outerio (Gondomar). Please find attached a photo of a CCGT power plant presently operating in Portugal.

Wind solution	
Description	250 new wind farms, with total installed capacity equal to 3800 MW.
Placement	Spread across the country, but with higher concentration in the inland North hills.
Characteristics	Each wind farm will have between 10 and 15 turbine, about 65 m high and may occupy an area of about 100 ha (1 km^2).
Examples	Presently there are about 1000 turbines operating in the mainland, some examples may be seen in Marão, Açor, Barroso among many others. Please find attached a photo of a wind power plant presently operating in Portugal.

PART I

We ask you now for please make **pairwise comparisons of the three solutions** with respect to some criteria:

1. Visual impact. This criterion is difficult to quantify and depends heavily on individual perception. It is associated with the aesthetic aspect, and it will be necessary to assess if the project will bring significant changes to the landscape and if these changes will reduce the visual quality of the region

a) The visual impact of the coal solution is ____ to the wind solution.

b) The visual impact of the coal solution is ____ to the gas solution.

c) The visual impact of the gas solution is ____ to the wind solution.

2. Noise level. This criterion is usually associated with sleeping disorders, interference with learning activities and general annoyance, caused by undesirable noise. It will be necessary to assess if the project will change the noise levels in the region.

a) The noise impact of the coal solution is ____ to the wind solution.

b) The noise impact of the coal solution is ____ to the gas solution.

c) The noise impact of the gas solution is ____ to the wind solution.

3. Impact on birds and wild life. This criterion is associated with problems like bird electrocution, collision mortality, reduction of available habitat, disturbance of nesting, alteration of migration habits and general habitat disturbances due the increase of human activity.

a) The impact on birds and wildlife of the coal solution is ____ to the wind solution.

b) The impact on birds and wildlife of the coal solution is ____ to the gas solution.

c) The impact on birds and wildlife of the gas solution is ____ to the wind solution.

4. Social acceptance. This criterion is associated with the way the project will be seen and accepted by the population in general. It may generate some resistance or on the other hand may be considered desirable.

a) The social acceptance of the coal solution is ____ to the wind solution.

b) The social acceptance of the coal solution is ____ to the gas solution.

PART II

We ask you now for please make **pairwise comparisons of the importance of the considered criteria**:

a) The visual impact is ____ to the noise level.

b) The visual impact is ____ to the impact on birds and wildlife.

c) The visual impact is ____ to the social acceptance.

d) The noise level is ____ to the impact on birds and wildlife.

e) The noise level is ____ to the social acceptance.

f) The impact on birds and wildlife is ____ to the social acceptance.

PART III

In January 2006, the electricity bill of an average Portuguese consumer was about 41 €/month (14 centon/kWh)

We ask you now for evaluate how much would you be willing to increase your average electricity bill, in order to contribute to the reduction of the atmospheric pollution:

Contact (email)	

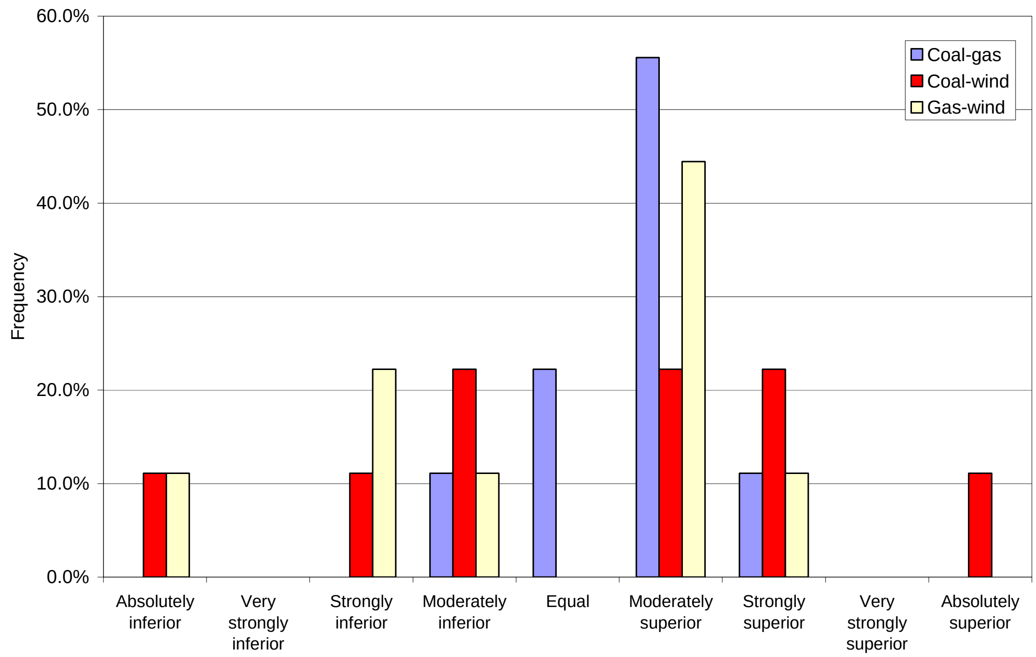
Comments:

Please send to paulaf@dps.uminho.pt

Thank you for your collaboration!

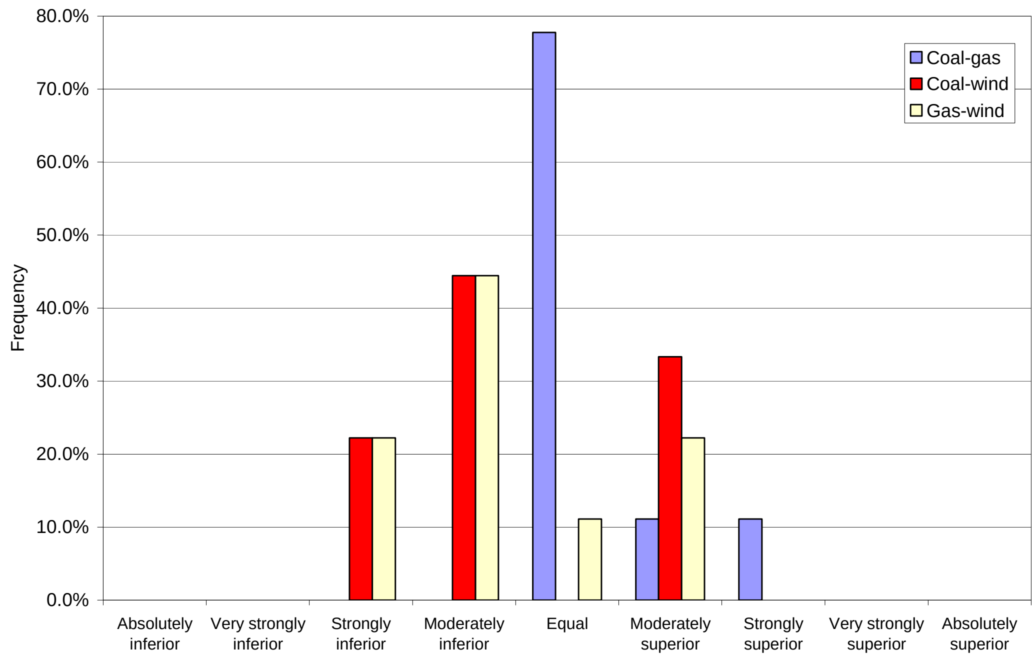
ANNEX 13

Pairwise comparison of the generation options against visual impact (1st round)



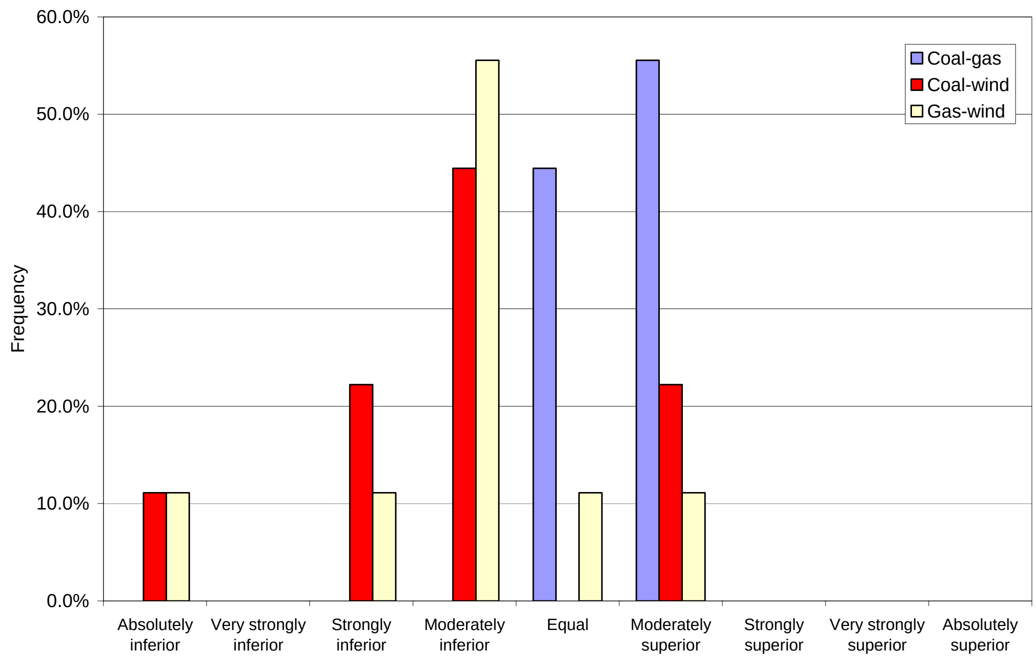
ANNEX 14

Pairwise comparison of the generation options against noise level (1st round)



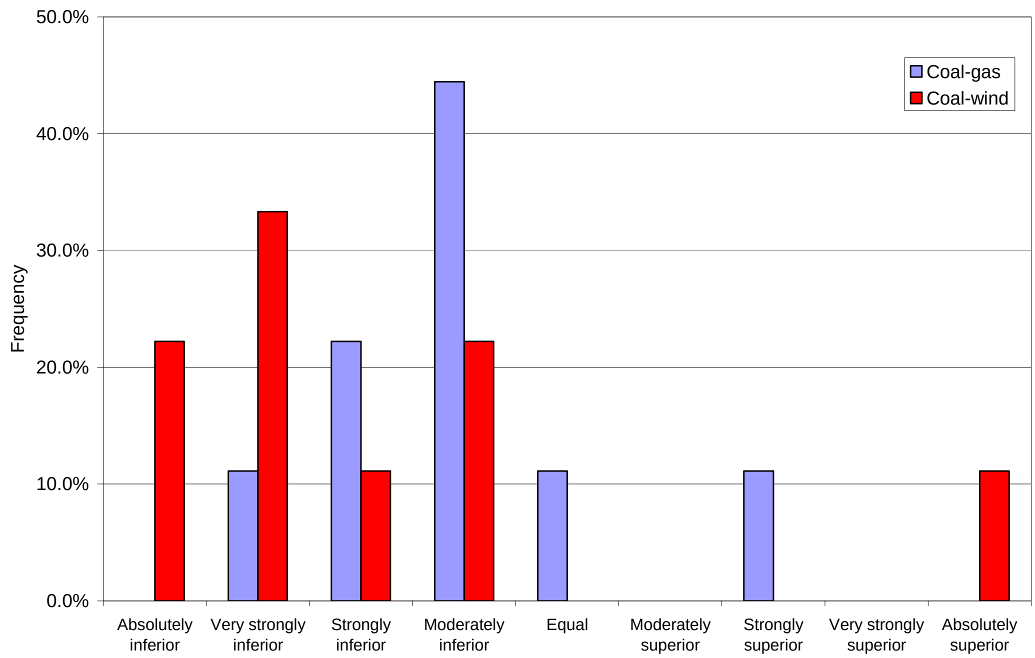
ANNEX 15

Pairwise comparison of the generation options against impact on birds and wildlife (1st round)



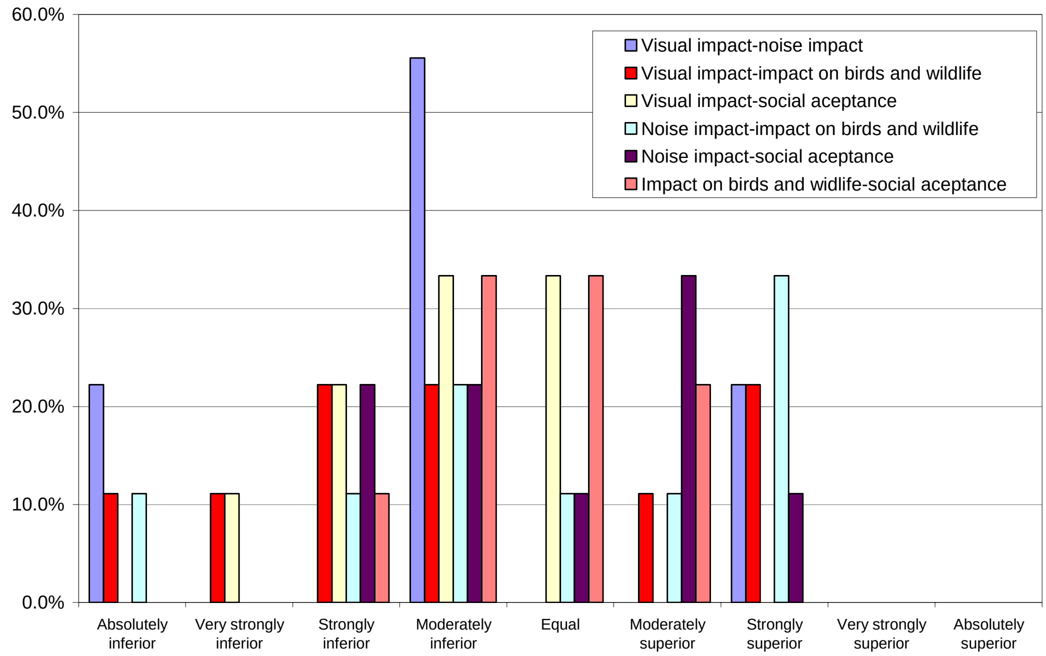
ANNEX 16

Pairwise comparison of the generation options against social acceptance (1^{st} round)



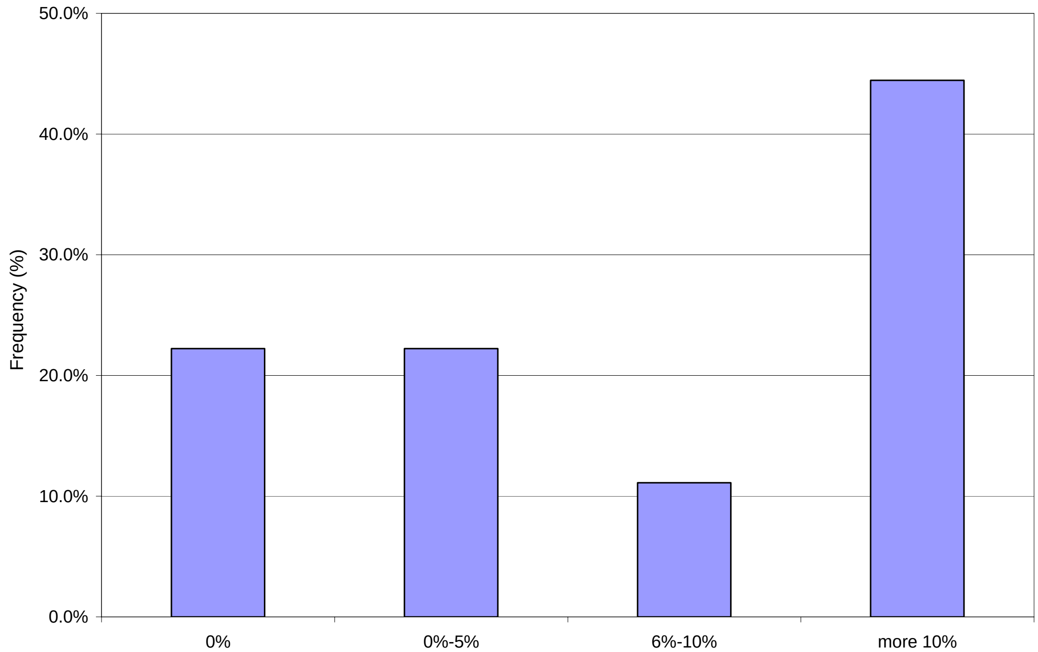
ANNEX 17

Pairwise comparison of the social criteria (1st round)



ANNEX 18

Willingness to pay for lower emissions (1st round)



ANNEX 19

Delphi questionnaire (2nd round)

EVALUATION OF THE IMPACTS OF DIFFERENT ALTERNATIVES FOR ELECTRICITY GENERATION

This is a multiple choice questionnaire, where the possible answers will appear when clicking in the grey fields.

Assume the necessity of increasing the available power in about 1000 MW. This may be accomplished by new coal, gas or wind power plants. The possible solutions may be described as follows:

Coal solution	
Description	2 new coal power plants, one with installed capacity equal to 700 MW and another one with installed capacity equal to 450 MW.
Placement	Close to large electricity consumption centres.
Characteristics	In each power station there will be one chimney 225 m high and one cooling tower. Each power plant may occupy an area of about 1.5 ha (0.015 km^2) and burns imported coal.
Examples	Presently two power stations operate in Portugal: one in Sines and another one in Pego. Please find attached a photo of a coal power plant presently operating in Portugal.

Gas solution	
Description	2 new combined cycle natural gas power plants, one with installed capacity equal to 660 MW and another one with installed capacity equal to 400 MW.
Placement	Close to large electricity consumption centres.
Characteristics	The 660 MW power station will have two chimneys. The 400 MW power station will have 1 chimney. All the chimneys will be 80 m high. Each power station will have a cooling tower. Each power station may occupy an area of about 1.5 ha (0.015 km^2). It burns imported natural gas.
Examples	Presently two CCGT operate in Portugal: one in Ribatejo (Carregado) and another one in Tapada do Outerio (Gondomar). Please find attached a photo of a CCGT power plant presently operating in Portugal.

Wind solution	
Description	180 new wind farms, with total installed capacity equal 3800 MW.
Placement	Spread across the country, but with higher concentration in the inland North hills.
Characteristics	Each wind farm will have between 8 and 10 turbine, about 65 m high and may occupy an area of about 2.5 ha (0.25 km^2).
Examples	Presently there are about 1000 turbines operating in the mainland, some examples may be seen in Marão, Açor, Barroso among many others. Please find attached a photo of a wind power plant presently operating in Portugal.

Comments from the experts:

The dimension of the wind farms suggested in the 1st round was excessive, according to the present characteristics of the available machines. The characterization of the wind solution was changed according to the comments received. Please find attached a picture from a more recent wind farm.

For the wind solution the installed power must be much higher than the average power needed. Due to wind fluctuations and intermittency, the average available power for electricity production on the wind solution is much lower than the installed power, which does not happen with either the coal or the gas solution.

1st quartile: 25% of the responses were equal or less than the category presented.
2nd quartile (median): 50% of the responses were equal or less than the category presented.
3rd quartile: 75% of the responses were equal or less than the category presented.

PART I

We ask you now for please make **pairwise comparisons of the three solutions** with respect to some criteria:

1. Visual impact. This criterion hardly may be quantified and depends heavily on the individual perception. It is associated with the aesthetic aspect, and it will be necessary to assess if the project will bring significant changes to the landscape and if these changes will reduce the visual quality of the region.

d) The visual impact of the coal solution is ______ to the wind solution.

Results from the 1st round:
1st quartile: **"4-moderately inferior"**
2nd quartile (median): **"6-moderartely superior"**
3rd quartile : **"7-stronlgy superior"**

Your answer to the first round was:

e) The visual impact of the gas solution is ______ to the wind solution.

Results from the 1st round:
1st quartile: **"3- strongly inferior"**
2nd quartile (median): **"6-moderartely superior"**
3rd quartile : **"6-moderartely superior"**

Your answer to the first round was:

Comment from the experts: The visual impact of a wind farm may be superior to the other solutions. However, some may assume this as a positive impact because it represents an image of clean energy production.

2. Noise level. This criterion is usually associated with sleeping disorders, interference with learning activities and general annoyance, caused by undesirable noise. It will be necessary to assess if the project will change the noise levels in the region.

a) The noise impact of the coal solution is ______ to the wind solution.

Results from the 1st round:
1st quartile: **"4- moderately inferior"**
2nd quartile (median): **"4- moderately inferior"**
3rd quartile : **"6-moderartely superior"**

Your answer to the first round was:

3. Social acceptance. This criterion is associated with the way project will be seen and accepted by the population in general. It may generate some resistance or on the other hand may be considered desirable.

a) The social acceptance of the coal solution is ______ to the wind solution.

Results from the 1st round:
1st quartile: **"2- very strongly inferior"**
2nd quartile (median): **"2- very strongly inferior"**
3rd quartile : **"4-moderartely inferior"**

Your answer to the first round was:

c) The social acceptance of the gas solution is to the wind solution. (new question)

PART II

We ask you now for please make **pairwise comparisons of the importance of the considered criteria**:

b) The visual impact is to the impact on birds and wildlife.

Results from the 1st round:
1st quartile: **"3- strongly inferior"**
2nd quartile (median): **"4- moderately inferior"**
3rd quartile : **"6-moderartely superior"**

Your answer to the first round was:

c) The visual impact is to the social acceptance.

Results from the 1st round:
1st quartile: **between "3- strongly inferior" and "4- moderately inferior"**
2nd quartile (median): **"4- moderately inferior"**
3rd quartile : **"5-equal"**

Your answer to the first round was:

d) The noise level is to the impact on birds and wildlife.

Results from the 1st round:
1st quartile: **between "3- strongly inferior" and "4- moderately inferior"**
2nd quartile (median): **between "4- moderately inferior" and "5-equal"**
3rd quartile : **"7- strongly superior"**

Your answer to the first round was:

e) The noise level is to the social acceptance.

Results from the 1st round:
1st quartile: **between "3- strongly inferior" and "4- moderately inferior"**
2nd quartile (median): **between "4- moderately inferior" and "5-equal"**
3rd quartile : **"6- moderately superior"**

Your answer to the first round was:

PART III

In January 2006, the electricity bill paid by an average Portuguese consumer was about 41 €/month (14 centon/kWh)

We ask you now for evaluate how much would you be willing to increase your average electricity bill, in order to contribute to the reduction of the atmospheric pollution:

Results from the 1st round:
- Median: "**between 6 and 10%**"
- 22% of the experts selected: **"0%"**
- 22% of the experts selected: **"up to 5%"**
- 22% of the experts selected: **"between 6 and 10%"**
- 22% of the experts selected: **"more than 10%"**

Your answer to the first round was:

Contact (email)	

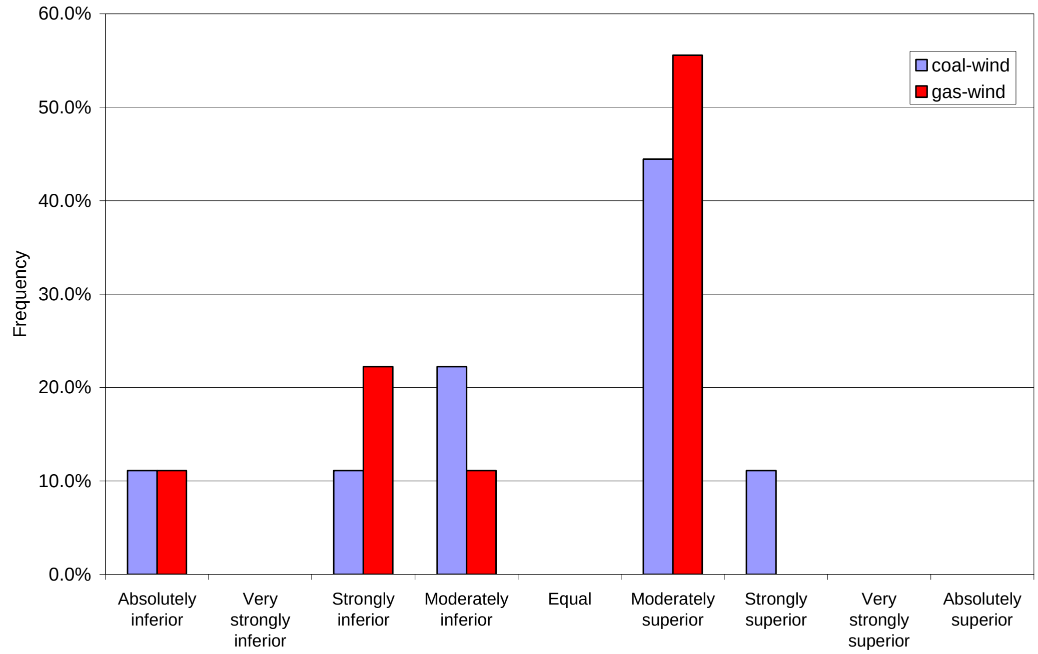
Comments:

Please send to paulaf@dps.uminho.pt

Thank you for your collaboration!

ANNEX 20

Pairwise comparison of the generation options against visual impact (2nd round)



Coal-wind

Rating	1	2	3	4	5	6	7	8	9
Change*	0	0	0	0	0	2	1	0	1

* Absolute difference in number seclecting rating, round 1-2.

Net change: 2
Number of participants: 9
Percent change: 22.22%

Gas-wind

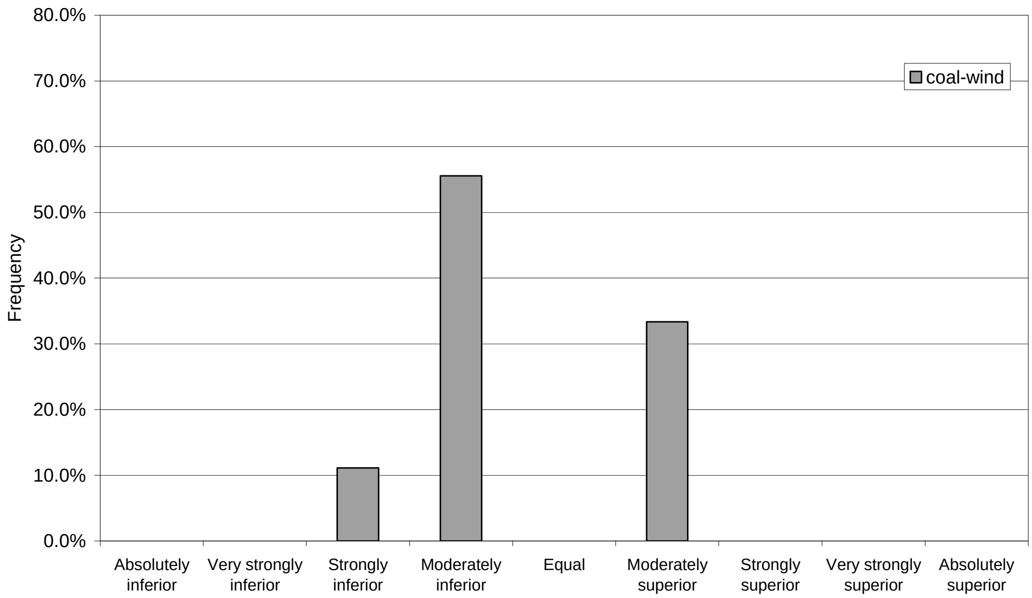
Rating	1	2	3	4	5	6	7	8	9
Change*	0	0	0	0	0	1	1	0	0

* Absolute difference in number seclecting rating, round 1-2.

Net change: 1
Number of participants: 9
Percent change: 11.11%

ANNEX 21

Pairwise comparison of the generation options against noise level (1st round)



Coal-wind

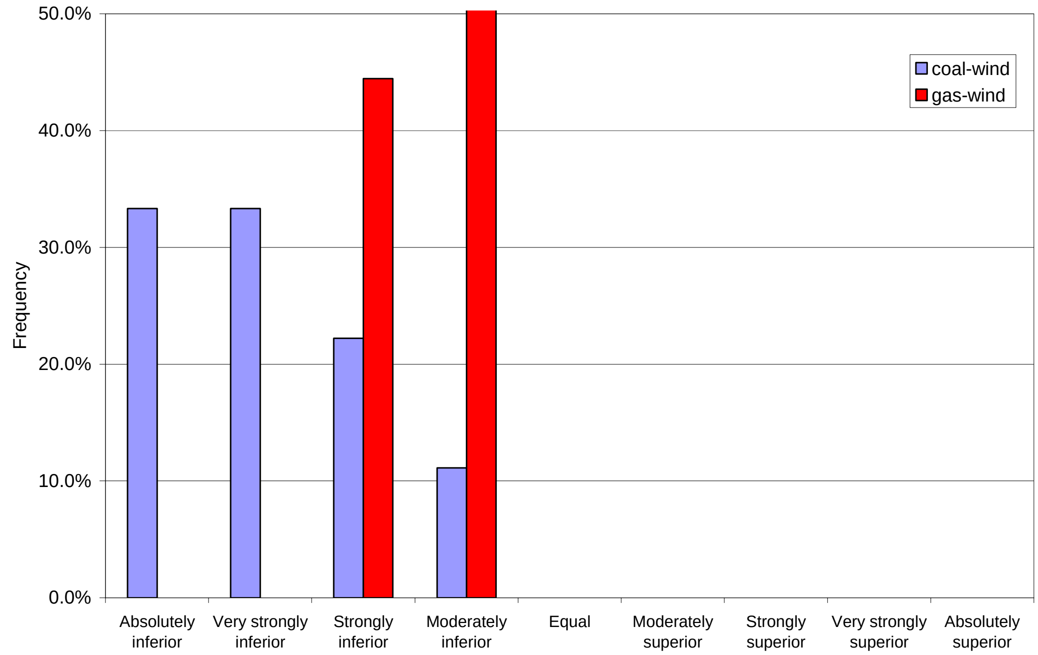
Rating	1	2	3	4	5	6	7	8	9
Change*	0	0	1	1	0	0	0	0	0

* Absolute difference in number seclecting rating, round 1-2.

Net change: 1
Number of participants: 9
Percent change: 11.11%

ANNEX 22

Pairwise comparison of the generation options against social acceptance (2nd round)



Coal-wind

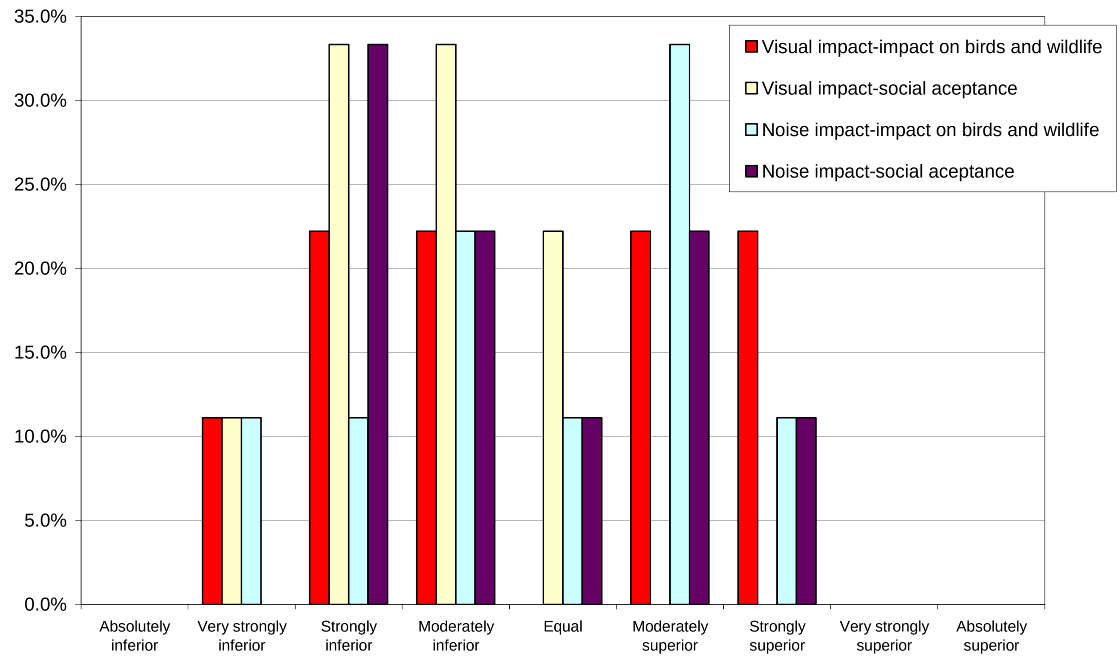
Rating	1	2	3	4	5	6	7	8	9
Change*	1	0	1	1	0	0	0	0	1

* Absolute difference in number seclecting rating, round 1-2.

Net change: 2
Number of participants: 9
Percent change: 22.22%

ANNEX 23

Pairwise comparison of the social criteria (2nd round)



Visual impact- impact on birds and wildlife

Rating	1	2	3	4	5	6	7	8	9
Change*	1	0	0	0	0	1	0	0	0

* Absolute difference in number seclecting rating, round 1-2.

Net change: 1
Number of participants: 9
Percent change: 11.11%

Visual impact- social acceptance

Rating	1	2	3	4	5	6	7	8	9
Change*	0	0	1	0	1	0	0	0	0

* Absolute difference in number seclecting rating, round 1-2.

Net change: 1
Number of participants: 9
Percent change: 11.11%

Noise impact- impact on birds and wildlife

Rating	1	2	3	4	5	6	7	8	9
Change*	1	1	0	0	0	2	2	0	0

* Absolute difference in number seclecting rating, round 1-2.

Net change: 3
Number of participants: 9
Percent change: 33.33%

Noise impact- social acceptance

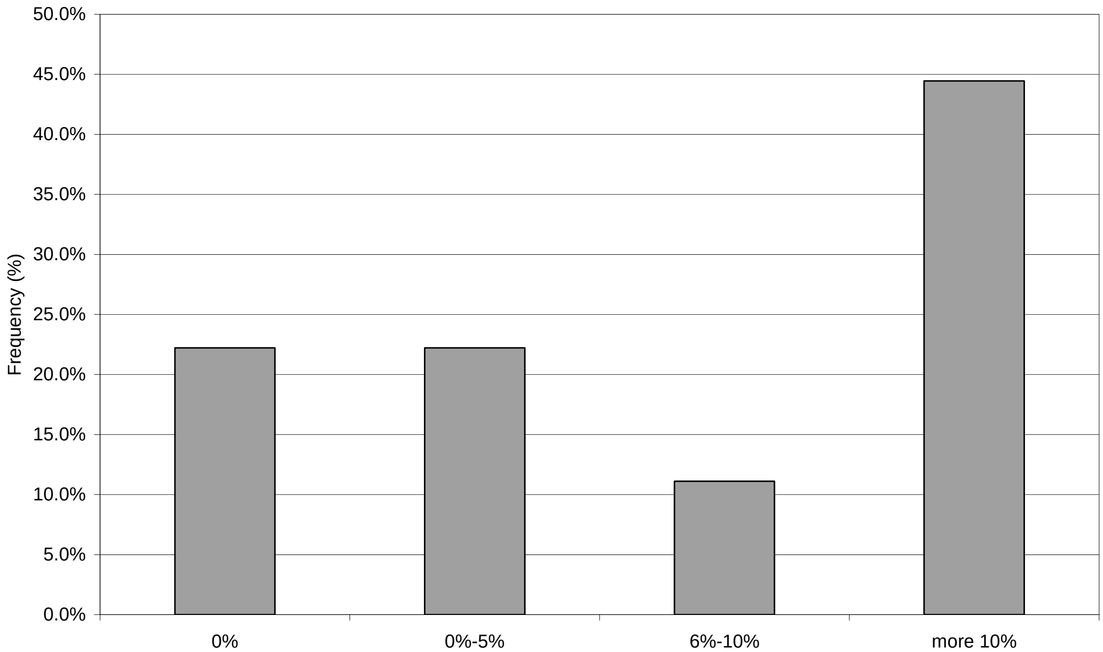
Rating	1	2	3	4	5	6	7	8	9
Change*	0	0	1	0	0	1	0	0	0

* Absolute difference in number seclecting rating, round 1-2.

Net change: 1
Number of participants: 9
Percent change: 11.11%

ANNEX 24

Willingness to pay for lower emissions (2nd round)



Noise impact- social acceptance

Rating	0%	0%-5%	6%-10%	>10%
Change*	0	0	0	0

* Absolute difference in number seclecting rating, round 1-2.

Net change: 0
Number of participants: 9
Percent change: 0%